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PREDICTING FIELD WATER BALANCE, CROP YIELD, AND THE ECONOMICS OF DRAINAGE UNDER VARIOUS CROPPING SYSTEMS USING DRAINMOD

BY

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A thesis submitted in partial fulfillment of the requirements for the

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PREDICTING FIELD WATER BALANCE, CROP YIELD, AND THE ECONOMICS OF DRAINAGE UNDER VARIOUS CROPPING SYSTEMS USING DRAINMOD

This thesis is approved as a creditable and independent investigation by a candidate for the Master of Science in Agricultural and Biosystems Engineering degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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DISCLAIMER

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ABBREVIATIONS

\$/ha/yr	Dollar per Hectare per Year
ASCE	American Society of Civil Engineers
CGDD	Cumulative Growing Degree Days
cm	Centimeter
CTD	Conductivity, Temperature, and Depth
d	Index of Agreement
ET	Evapotranspiration
ET_o	Reference Evapotranspiration
GDD	Growing Degree Days
GIS	Geography Information System
GPS	Global Positioning System
HPRCC	High Plains Regional Climate Center
Kg/ha	Kilogram per Hectare
MAE	Mean Absolute Error
$Mgha^{-1}$	Mega-grams per hectare
mm/day	Millimeter per day
NO_3-N	Nitrate Nitrogen
NRCS	Natural Resources Conservation Service

NSE	Nash-Sutcliffe Efficiency
PET	Potential Evapotranspiration
Ref. ET	Reference Evapotranspiration
SD	South Dakota
SDOC	South Dakota Office of Climatology
SDSU	South Dakota State University
SERF	South East Research Farm
SEW	Excess Soil Water
USDA	Unite States Department of Agriculture
vol	Volume
WTD	Water Table Depth

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ABSTRACT

PREDICTING FIELD WATER BALANCE, CROP YIELD, AND THE ECONOMICS OF DRAINAGE UNDER VARIOUS CROPPING SYSTEMS USING DRAINMOD

SHAILENDRA SINGH

2016

Subsurface drainage received considerable attention during the recent few years in South Dakota. While subsurface drainage is a widely accepted water management practice for increasing crop yield, research implicated tile drainage in surface and groundwater quality problems. Conservation practices such as crop rotation and controlled drainage may decrease tile flows and improve water quality. A two-year (2014-2015) subsurface drainage study was conducted at South Dakota State University Southeast Research Farm (SERF) near Beresford, South Dakota to evaluate the effectiveness of selected conservation practices in reducing drainage volume and nitrate losses. Six experimental plots, under corn-soybean rotation, divided into drained and undrained plots, were monitored for baseline data (i.e. drainage discharge, water table depth, infiltration, bulk density, and rainfall) collection. DRAINMOD was used with the baseline data to quantify the long-term hydrologic impacts of subsurface tile drainage on field water balance for different drainage conditions (conventional drainage, controlled drainage, and undrained condition) and cropping practices.

Long-term simulations for 12-year period (2004-2015) were conducted to predict annual and monthly water balance, crop yield response under conventional drainage, controlled drainage, and undrained conditions for continuous corn, corn-soybean, soybean-corn, corn-wheat, wheat-corn, soybean-wheat, and wheat-soybean cropping practices. Average annual subsurface drainage results for continuous corn, corn-soybean, soybean-corn, corn-wheat, soybean-wheat, wheat-corn, and wheat-soybean cropping practices under controlled drainage showed drainage volume reduction of 28%, 24%, 24%, 52%, 37%, 54%, and 40%, respectively, compared to conventional drainage. Similarly, average annual surface runoff results for continuous corn, corn-soybean, soybean-corn, and wheat-soybean rotation under conventional drainage indicated runoff volume reduction of 72%, 75%, 71%, and 76%, respectively, compared to undrained conditions, and under controlled drainage runoff volume reductions for same cropping practices were 65%, 68%, 65%, and 66%, respectively, compared to undrained conditions. Average monthly water balance showed high ET water loss during the month of May to August and high drainage water loss during month of May and June. Drainage volume reduction of 57.0% was observed in June for wheat-corn rotation under controlled drainage compared to conventional drainage. Likewise, surface runoff volume reduction of 86.7%, and 70.0% in conventional drainage and 86.6% and 63.3% in controlled drainage for May and June was observed in soybean-corn rotation compared to undrained conditions.

Predicted relative crop yield percentage showed high yield in soybean-corn, and corn-soybean rotation under conventional drainage and controlled drainage compared to all other cropping practices. Relative crop yield for soybean-corn and corn-soybean under conventional drainage was 81.6% and 80.9%, respectively, and under controlled drainage, relative yield was 81.8% and 81.7%, respectively. Crop relative yield results indicated better yield for soybean-corn followed by corn-soybean production under both conventional and controlled drainage compared to undrained conditions but economic analysis results showed better net annual return form soybean-corn rotation under controlled drainage compared to all other cropping practices in controlled drainage, conventional drainage, and undrained conditions.

1 INTRODUCTION

1.1 Background

Over the past few decades, subsurface (tile) drainage has gained popularity as a proven technology for mitigating water logging and salinity problems, improving soil conditions, and reducing risks of crop failure (Sands et al., 2008; Skaggs et al., 1982). In United States and many parts of the world, subsurface drainage facilitated reclamation of millions of hectares of marginal farmland into highly productive and profitable lands (Nijland et al., 2005). It continues to be a common practice for improving soil conditions to support crop production in areas with high water table and water logging issues. Under saturated soil conditions, the level of oxygen exchange between soil and atmosphere decreases, resulting in low oxygen availability in the soil profile for crop root use, decreases in crop mineral intake, and availability of nutrients (Sands, 2001; Schilfgaarde, 1983). Subsurface drainage allows farmers to have timely field operations, including seedbed preparation, planting, harvesting, use of machinery, and a wide choice of crop varieties and cropping systems (Spaling and Smit, 1995). While subsurface drainage has proven agronomic benefits ((Nijland et al., 2005; Skaggs et al., 1982), it alters field hydrology and water quality by removing water and dissolved pollutants from the soil profile (Sands, 2001). Continued understanding of subsurface drainage impacts on field hydrology is required to support watershed management decisions, address off-site environmental impacts, and implement best management practices.

1.2 History of Subsurface Drainage

Subsurface drainage has been extensively used in the United States for more than 100 years. Previous studies reported that subsurface drainage technology began in United States mainly in the Upper Midwest in mid-1800s' by the European settlers (Pavelis, 1987; Sands, 2001; Zucker and Brown, 1998). The first subsurface drainage was a clay tile with horseshoe pattern imported from Scotland into USA by a European native farmer John Johnston in 1835 (Beauchamp, 1987; Sheler, 2013; Weaver, 1964). These clay tiles were entirely hand made from rolled plastic clay sheets having thickness of about half inch which were cut into rectangular shape of desired size (Pavelis, 1987; Sheler, 2013). Beginning with simple horseshoe drains, tile drainage development passes through different modification stages which include horseshoe drains on sole plates, flat-bottomed D-shaped drains, and finally round pipes (Stuyt et al., 2005).

Manufacturing of concrete (mixture of sand and cement) drainage pipe started in United States in 1862 using a machine developed by David Ogden (Pavelis, 1987; Schwab and Fouss, 1999) . The machine was capable of making concrete tile drains having inside diameter ranging from 2.25 inches to 24 inches (Pavelis, 1987). In 1950's American Society of Testing Material (ASTM) approved the specifications for concrete tile drains to ensure manufacturing of good-quality clay and concrete tile drains (Pavelis, 1987). In the early 1960's, manufacturing corrugated plastic tubing was initiated using polyethylene and polyvinyl resins (Nijland et al., 2005; Pavelis, 1987). This initiation added advancement in the development and usage of subsurface drainage technology. The plastic pipes were more cost effective and easier to handle compared to clay and concrete tiles (Nijland et al., 2005). The use of plastic also eliminated problems associated with handling and shipping clay and concrete tile, and tile alignment during installation.

With development in subsurface drainage design and manufacturing materials, different types of trenching machines were brought into use for installing subsurface drainage systems. From 1945 to1960 two types of trenching machines were used for installing tile drainage; these are wheel-type and ladder or chain type (shown in Figure 1)(Pavelis, 1987). By the 1970's, high performance trenchless drainage pipe installing machines came into practice (Sheler, 2013). These machines provided laser technology for maintaining appropriate grade during subsurface drain installation. In recent years, the laser systems have been replaced with GPS guided plow control systems, which integrate sensors to control the grade and depth during the subsurface drain installation process.

Subsurface drainage has played a significant role in agricultural modernization and US westward expansion. After approval of Swamps Lands Acts of 1849 and 1850, subsurface drainage installation in United States received high priority in the areas having swampy land and high water table (Pavelis, 1987). As of 1985, about 43 million ha (25% of 170 million ha) of cropland in the United States were designated as wet soils and a total of 31 million ha (28 million non-irrigated and 3 million irrigated) of these soils have been artificially drained to the extent that they are classified as prime farmland (Pavelis, 1987; Skaggs et al., 1994). According to the United States Department of Agriculture (USDA, 1985), about 25% of agricultural lands in USA require artificial drainage systems to support and improve crop production.

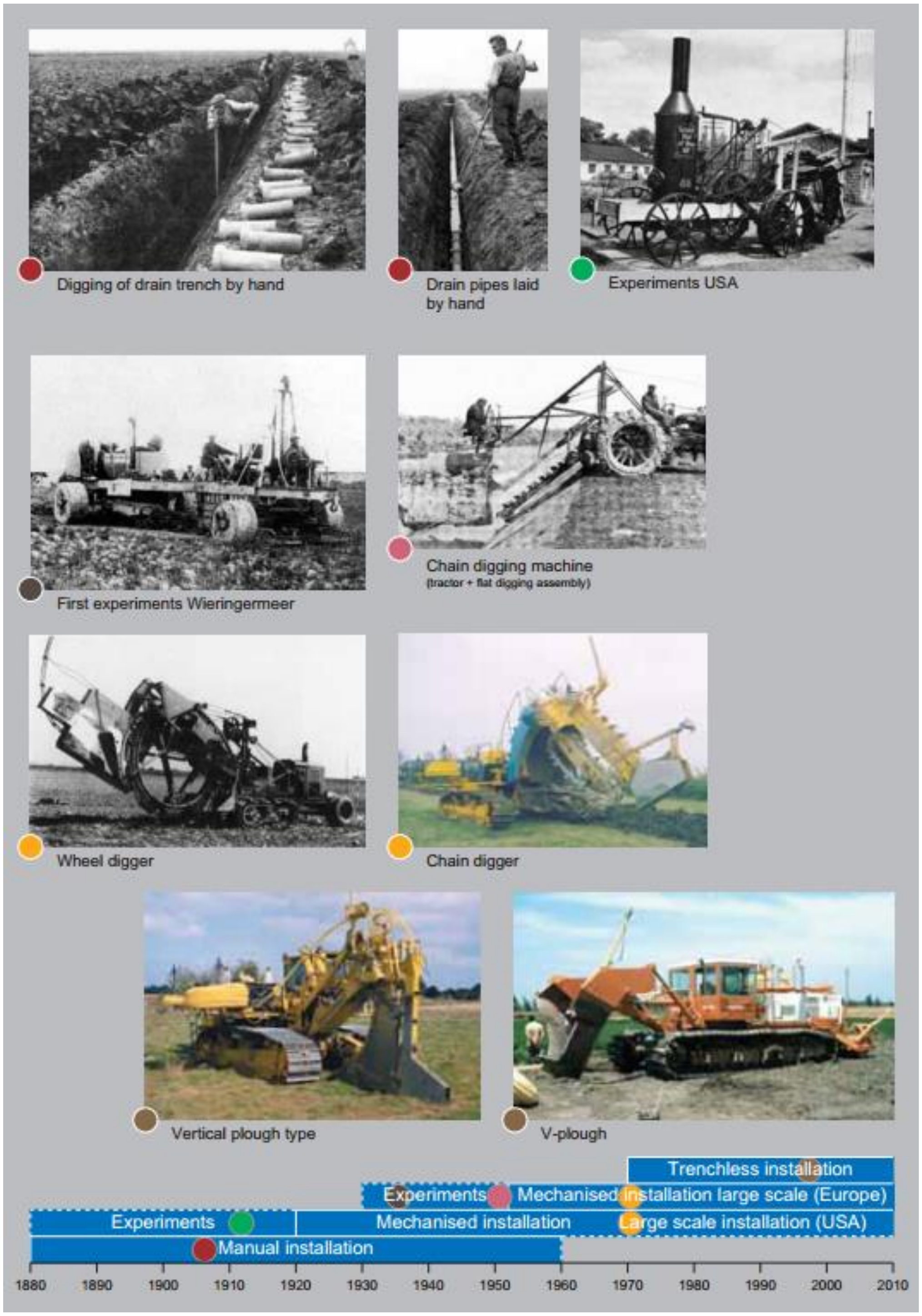


Figure 1. Mechanization of Subsurface Drainage (Nijland et al., 2005).

1.3 Problem Statement

Although the purpose of subsurface drainage is to provide optimum soil moisture and water content to foster higher crop yields, subsurface drainage alters hydrology and may contribute to water quality problems (Randall and Vetsch, 2002; Rivett et al., 2008). Previous studies have linked subsurface drainage to eutrophication in the Great Lakes and hypoxia in the Gulf of Mexico (Goolsby et al., 2001). For example, agricultural headwater streams in Indiana and other Midwestern states (e.g. Iowa, Illinois, and Ohio) have been identified as contributors of nitrate-nitrogen (nitrate-N) to the Mississippi River, mainly due to high concentrations of NO_3-N (exceeding 10 mgL^{-1}) in these headwater streams as shown in Figure 2 (Ahiablame et al., 2011; David et al., 2010; Pellerin et al., 2014; Petrolia and Gowda, 2006). Research has also linked subsurface drainage to increased infiltration, decreased annual evaporation, lowered water table, and increased baseflow and erosion (Larson and Moore, 1980), leading to changes in hydrology (Naz et al., 2005).

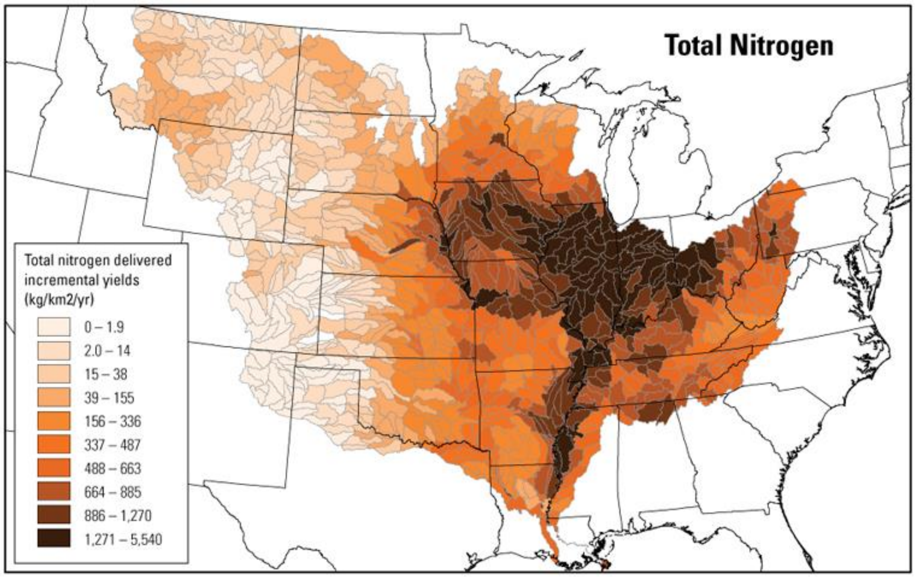


Figure 2. Nitrogen delivery to the Gulf of Mexico (Robertson et al., 2009).

In South Dakota, especially in the eastern part of the state, subsurface drainage has received considerable attention in recent years, due to increasing precipitation, high land and agricultural commodity prices, and improved technology for both fabrication and installation of subsurface drainage (Dahlseng, 2013). Expansion of subsurface drained lands may lead to off-site environmental impacts resulting both from nutrient leaching and hydrologic variation in field water budgets. However, adoption of conservation practices such as controlled drainage and various crop management practices can help minimize environmental impacts of subsurface drainage. Hydrology of drained lands changes widely with climate, soils, and crop management conditions (Sands, 2002). Therefore, there is a need to understand the effects of crop management combined with subsurface drainage practices on field water budgets and crop growth in the Upper Midwest.

1.4 Objectives

The overall goal of this study is to increase understanding of the benefits and limitations of different drainage conditions and cropping practices in eastern South Dakota. The specific objectives are:

a. Predict field water balance under different cropping systems in conventional drainage, controlled drainage, and undrained conditions.
b. Assess crop yield responses to these drainage conditions.
c. Evaluate the economic impacts of subsurface drainage.

Various drainage scenarios were evaluated with DRAINMOD in this study to provide some insight for maximizing the economic benefits of drainage and minimizing potential off-site environmental impacts.

1.5 Significance of the Study

It is well documented that subsurface drainage alters field hydrology and is a major contributor to off-site environmental problems (Cooke et al., 2008; Kalita et al., 2007; Skaggs et al., 1994; Strock et al., 2010). However, continued understanding of subsurface drainage impacts on water table variation, crop yield, and associated economic response under varying drainage conditions would allow farmers and stakeholders to make timely decisions and adopt appropriate strategies to improve productivity and reduce environmental impacts subsurface drainage. This study focuses on evaluating different drainage and cropping practices to quantify the impacts of subsurface drainage on field water balance and crop yield.

2 LITERATURE REVIEW

2.1 Subsurface Drainage

Subsurface drainage is a network of perforated pipes installed below the soil surface (as shown in Figure 3), generally at depth of 1 m to 2 m with a purpose of removing excess soil water from the crop root zone (Fraser et al., 2001). Subsurface drainage provides a pathway for excess water to leave the soil profile by quickly removing excess water from the soil, thereby increasing infiltration capacity of the soil (Figure 4). Unsaturated soil (lower water table) facilitates prominent exchange of oxygen in the soil profile that helps to quickly warm up the soil and promotes higher nutrient intake, better microbial activities in the soil matrix, and roots propagation (Sheler, 2013). Crop roots with better nutrient intake and favorable growth environment have healthier and deeper roots with better yield potential.

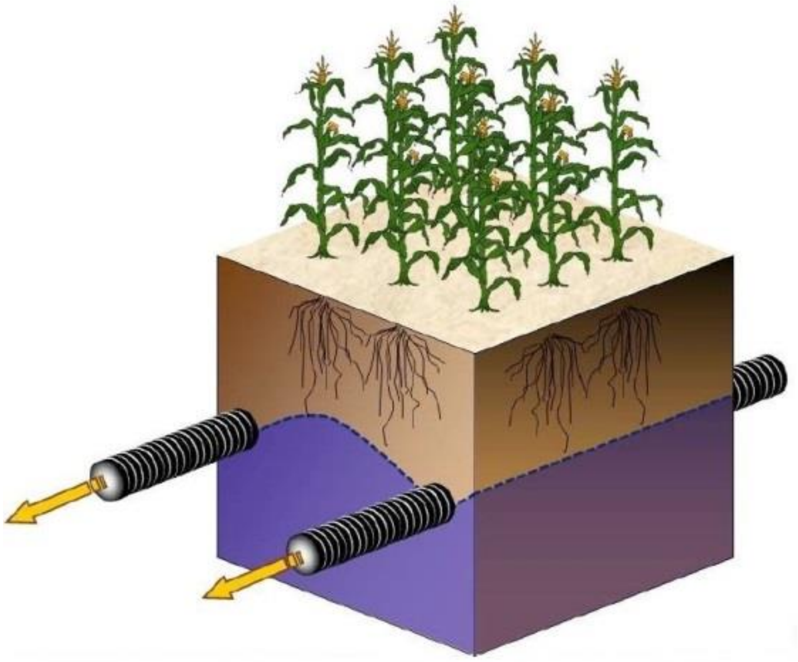


Figure 3. Subsurface drainage installed in field conditions (Sands, 2002).

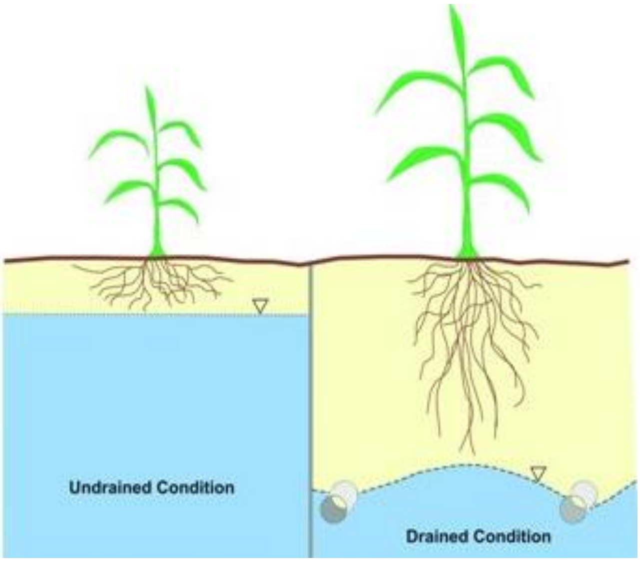


Figure 4. Water table depth under drained and undrained conditions (Sands, 2002).

2.1.1 Drainable water

Water movement from the soil surface into the soil profile is a complex phenomenon and requires in-depth understanding of different components associated with it. According to Darcy's law, water moves from high potential to low potential (Dingman, 2002). In soil profile, water is held in micropores by the action of capillarity and the maximum water that the soil can hold without any free drainage is called field capacity. This field capacity determines the amount of water available for plant use, and the addition of any excess water above field capacity results in eventual soil saturation. This excess water, also called drainable water or gravitational water, is loosely held in the soil profile and moves under the influence of gravity to the subsurface drains (Sands, 2001). There are various other factors that influence water movement in the soil profile. These include soil permeability, drain spacing, drain depth, and drain size. A schematic diagram is presented in Figure 5 representing different forms of water availability in the soil profile.

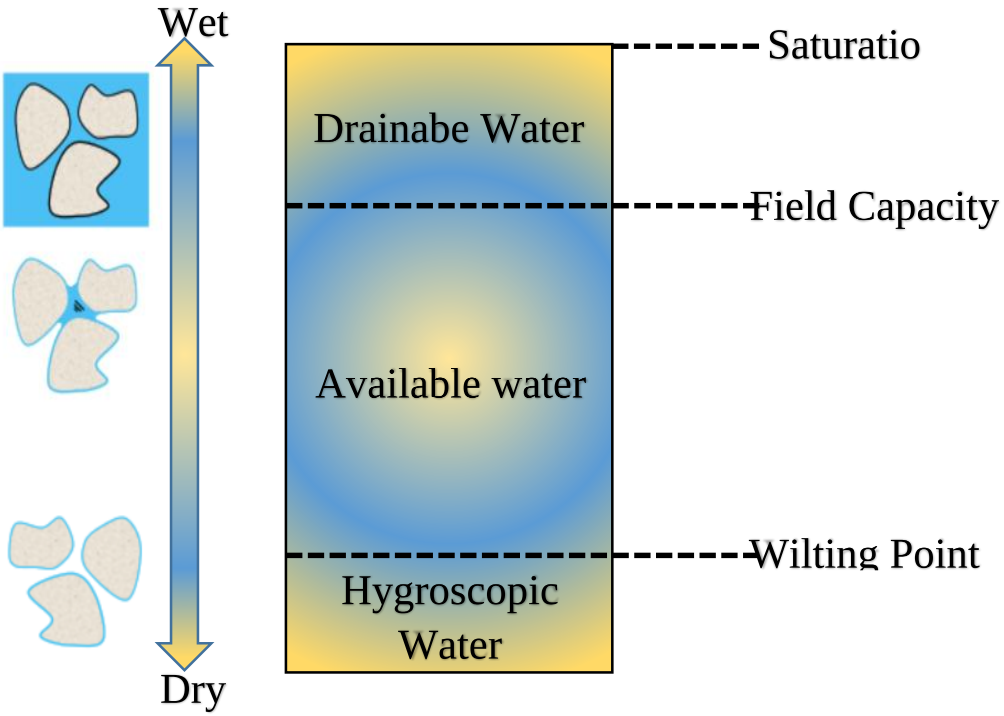


Figure 5. Types of soil water in the soil profile (Sands, 2001).

To understand flow mechanisms of subsurface drainage, it is important to understand the methods and sources through which subsurface drains receive water. Subsurface drainage receives water through three different mechanisms which are: (a) surface intake or direct inlet, designed to control ponding on the soil surface; (b) groundwater flow of drainable or gravitational water (i.e. saturation conditions); and (c) preferential/macropore flow (Franz et al., 2014). This mechanism is illustrated in Figure 6. However, these three pathways of transmitting water to the subsurface drains vary according to site, soil and climatic conditions. The majority of water received by subsurface drains in agricultural fields is mainly gravitational water. For example, a study on estimating preferential flow to a subsurface drainage system using tracer test conducted at Iowa State University showed that on average 98% of the flow was gravitational water and only 2% of flow was preferential flow (Everts and Kanwar, 1990). The other most important factor on which amount of water drained by the subsurface drainage depends is drainable porosity (drainable pore space) and is expressed as:

$$\text{Drainable Water (depth)} = \text{Drainable Porosity (\%)} \times \text{Drop in WT (depth)} \times 100 \quad (1)$$

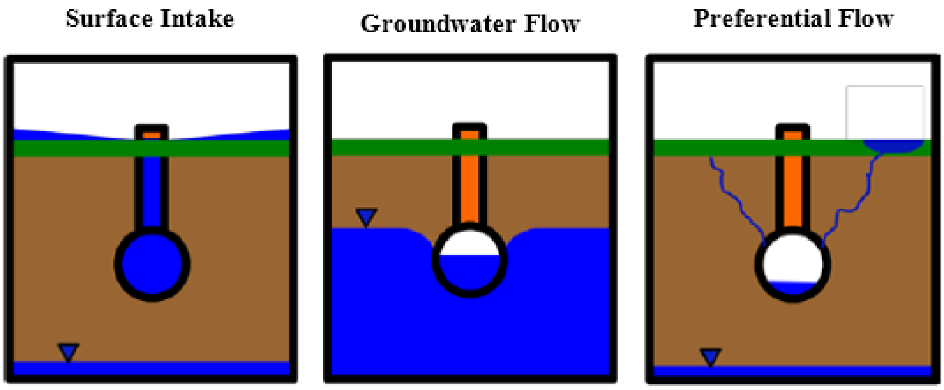


Figure 6. Three mechanisms through which subsurface drains receive water (Franz et al., 2014).

Drainable porosity is defined as the percentage of air filled pore spaces present in the soil profile at field capacity and is mainly influenced by the soil type, texture and structure (Sands, 2001). Table 1 shows drainable porosity for different types of soil textures.

Table 1. Different soil textures and respective drainable porosities (Sands, 2001)

Soil Texture	**Field Capacity (% by vol.)**	**Wilting point (% by vol.)**	**Drainable porosity (% by vol.)**
Clay, clay loam, silty clay soils	30-50%	15-24%	3-11%
Loam soil (well structured)	20-30%	8-17%	10-15%
Sandy soil	10-30%	3-10%	18-35%

2.1.2 Design of subsurface drainage

Subsurface drainage is primarily designed for lowering the water table or removing excess water from the soil profile, thereby providing better trafficable conditions for field operations, including planting and harvesting, and reducing excess water stress on the plants (Kalita et al., 2007; Skaggs et al., 1994). There are various factors that influence drainage design. These are field management, soil drainage characteristics, cost, environmental concerns, and existing drainage infrastructure (Strock et al., 2010). Drainage intensity and drainage placement are the two most influencing drainage design variables.

2.1.2.1 Drainage Intensity:

Drainage intensity determines whether a drainage system is capable of lowering the table to an extent that is beneficial to crop growth within a period of 24 to 48 hours of excess precipitation (Strock et al., 2010). It greatly influences drainage flow rate and pollutant loads in the drainage water. In general, subsurface drain depths range from 0.6 to 1.5 m and drain spacing varies from 10 to 100 m. Studies conducted in Minnesota showed reduction of 20% and 18% in both drainage volume and nitrate loads for shallow drainage systems compared to deeper drainage systems (Sands et al., 2008). Likewise, a study conducted in Indiana showed that closely spaced drains result in higher nitrate loading primarily influenced by the high volume of water drained (Kladivko et al., 1991). It is therefore, necessary to design drainage intensities to provide adequate drainage for optimum site benefits. Table 2 shows a general recommendation for drain lateral spacing and depth for different soil types.

Table 2. Recommended lateral spacing and depth (Wright and Sands, 2001)

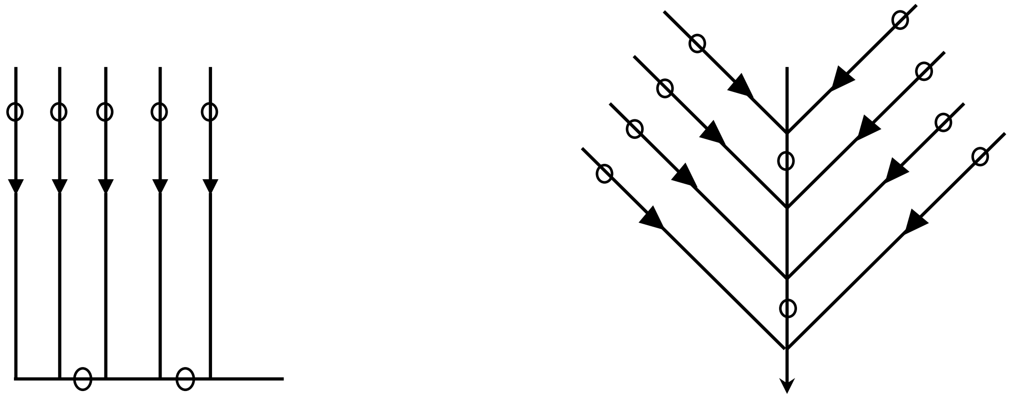
Soil Type	**Soil Permeability**	**Drain Spacing (ft) for:**			**Drain Depth (ft)**
		Fair Drainage	**Good Drainage**	**Excellent Drainage**	
Clay loam	Very low	70	50	35	3.0-3.5
Silty clay loam	Low	95	65	45	3.3-3.8
Silt Loam	Moderately low	130	90	60	3.5-4.0
Loam	Moderate	200	140	95	3.8-4.3

Sandy loam	Moderately high	300	210	150	4.0-4.5

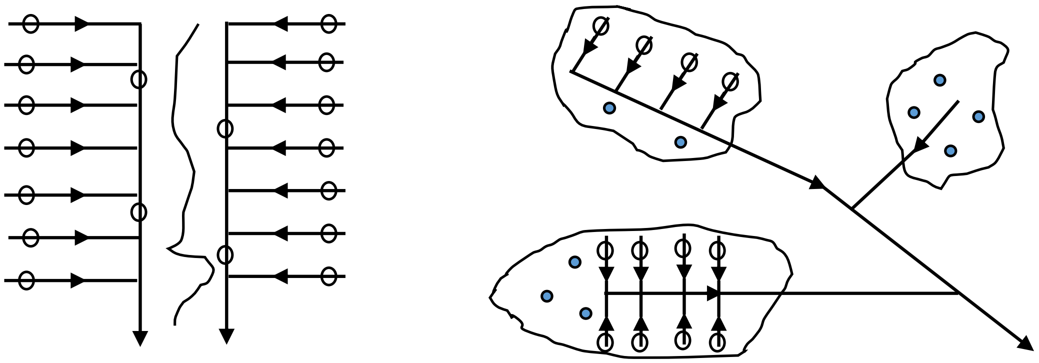
It is very critical to determine the optimal drain spacing for a soil when evaluating the subsurface drainage system economics. A subsurface drainage study conducted in Butelerville, Indiana, on poorly drained Clermont silt loam soil to determine the effect of three drain spacings (5 m, 10 m, and 20 m) compared with undrained control (40 m) on corn growth and grain showed that yearly corn growth, grain yield, and grain moisture content were significantly different at different drain spacings, mostly in the wider drain spacing (20 m) in comparison to narrower spacings (5 m and 10 m) and undrained control plot (Kladivko et al., 2005). A similar study conducted in Minnesota for predicting the impacts of drain spacing and drain depth on NO_3-N loss from agricultural fields showed that reducing drain depth from 1.5 m to 0.9 m for drain spacing of 40 m can reduce NO_3-N losses by 31%, while increasing drain spacing from 27 m to 40 m for drain depth of 1.5 m can reduce NO_3-N losses by 50% (Nangia et al., 2010).

2.1.2.2 Drainage System Layout

The other important consideration required in subsurface drainage design is determining system layout capable of providing adequate and uniform drainage of a field. Field topography, elevation, and location of field outlet(s) are generally the major factor considered in drainage system layout planning (Wright and Sands, 2001). Field topography maps are used to locate potential outlet points in the field. There are number of ways of creating field topography maps which includes standard field topography survey, GIS, GPS or laser measurements. Topography map helps in identifying field grades, high or low spots, and outlet alternatives.



Parallel Herringbone



Double Main Targeted

Figure 7. Different drainage system layout alternatives (Wright and Sands, 2001).

There are different drainage system layouts practiced based on the field topography and outlet location. The most commonly used layout outlet alternatives are parallel, herringbone, double main, and targeted (Figure 7). When choosing system layout for a particular field, it is recommend to place the field laterals or drain laterals on contours to maintain a uniform depth and achieve improved drainage uniformity (Panuska, 2012). It is also recommended that the collector drains or mains be positioned along the steeper grades to facilitate quicker discharge from the field laterals (Hofstrand, 2010; Wright and Sands, 2001).

2.1.3 Agronomic and economic benefits of subsurface drainage

Subsurface drainage has potential to reduce the risk of crop failure due to excess water stress and provides more uniform crop production amidst climate variability. It provides better trafficability conditions for timely field operations including planting and harvesting, increases soil aeration and promotes microbial activities within the soil profile which helps in improving soil texture and structure (Fraser and Fleming, 2001; Gardner et al., 1994).

Research studies conducted in Indiana and Ohio showed that subsurface drainage increased annual corn yield by 0.9 to 1.4 Mg ha^{-1} and 1.3 to 1.9 Mg ha^{-1}, respectively (Zucker and Brown, 1998). Another study conducted in Southeast Indiana showed increase in corn yields by 0.3 to 0.6 Mg ha^{-1} (Kladivko et al., 2005). A study on controlled drainage (drainage water management) conducted in North Carolina showed increase in corn and soybean yields by 11% and 10%, respectively, over conventional drainage (Poole et al., 2011). A similar drainage water management study conducted in Iowa showed soybean yield increase of 8% (Jaynes, 2012).

2.1.4 Hydrology

2.1.4.1 Soil-Water Storage Capacity and Surface Runoff

Subsurface drainage increases temporary water storage space in the soil profile compared to undrained fields (Fraser and Fleming, 2001; Sands, 2002). Research involving monitoring of five storm events in North Carolina showed that subsurface drainage increased storage capacity of the soil by continually removing excess or gravitational water from the soil profile (Skaggs and Broadhead, 1982). Increase in storage space facilitates more water infiltration into the soil profile, resulting in reduction in surface runoff rates (Natho-Jina et al., 1987; Skaggs et al., 1994). In western Oregon, measurement of three watershed runoff and suspended sediment load suggested that subsurface drainage increases the infiltration capacity of the soil by lowering water table quickly resulting in decrease in surface runoff, except during prolong precipitation condition exceeding drainage system capacity (Istok and Kling, 1983).

2.1.4.2 Peak Discharge Rates

Improved subsurface drainage reduces surface runoff and lowers peak discharge rates in poorly drained soils compared to sites that are primarily dependent on surface drainage (Skaggs et al., 1994). The amount of reduction in peak discharge rate depends on the initial field conditions such as initial soil moisture level and precipitation characteristics (King et al., 2014). For example, a study conducted by Skaggs and Broadhead (1982) found 20% and 87% reduction in peak flows in two soils having initial conditions very wet and dry, respectively, prior to precipitation. Other similar studies also showed that initial soil moisture conditions present in the field greatly influences peak flow rates of drained fields (Larson and Moore, 1980; Natho-Jina et al., 1987). A study involving four drainage water management practices; conventional, improved subsurface (modified drainage intensity), and two types of controlled drainage (2 different weir levels) applied on two North Carolina muck soils showed higher reduction in peak flow rates in large watersheds compared to smaller watersheds having improved drainage systems. Based on a three year return period storm, improved drainage reduced peak flows compared to conventional drainage from 101 to 28 mm/day on a 8.1 ha field, from

68 to 20 mm/day on a 130 ha area, from 30 to 15 mm/day on a 1036 ha area, and from 20 to 13 mm/day on a 6216 ha watershed (Konyha et al., 1992).

There are other factors that influence peak discharge rates of drainage systems. These are control structures, drain spacing, soil types, and site conditions (Cooke et al., 2008; Skaggs et al., 1994; Skaggs et al., 2012a). For example highly permeable soils may increase peak discharge by accelerating drainage discharge rate (Wiskow and van der Ploeg, 2003). Soils with high permeability enhance preferential flow, thereby promoting greater water infiltration through the preferential pathways (Fan et al., 2013). During a particular rainfall event, the raised weir in the control structure at the outlet point retains water within the laterals and soil profile, delaying the timing and reducing outflow duration and rate (Amatya et al., 2000).

Drain spacing used during design of drainage systems has been found to have an impact on peak flows. In Iowa, a study conducted on two soil types, Webster and Canisteo, showed that 25 m drain spacing used for drainage depth of 1.05 m and intensity of 0.46 cm/day can optimally reduce the drainage discharge (Singh et al., 2006). In poorly drained soils, decreasing drain spacing initially decreases the peak flow (Sloan, 2013). However, as decrease in drain spacing reaches some optimal point, peak flow increases because the hydraulic gradient to the drains gets steep and drainage discharge rate becomes fast (Robinson, 1990).

2.1.4.3 Seasonal and Annual Flows

Recent research suggests that streamflow increased in part due to increase in agricultural drainage discharge (Schilling and Libra, 2003). Seasonal and annual water yields, and runoff ratio have increased more than 50% since 1940 in 11 out of 21 watershed across Minnesota that experienced large land-use change and increased installation of subsurface drainage (Schottler et al., 2014). Subsurface discharge was assumed to contribute about 0% to 90% of watershed discharge during winter and spring months and about 40% on annual basis was reported in the Strawberry Creek Watershed, Maryhill, Ontario (Macrae et al., 2007). Other researchers showed that subsurface discharge contribution to streamflow varies with seasons. For example, two different research studies conducted in Ontario and Quebec region of Canada showed that subsurface drainage comprises fairly large portion of streamflow during the spring and winter seasons compared to the summer and fall seasons (Eastman et al., 2010; Macrae et al., 2007).

2.1.4.4 Drainage Water Management and Crop productivity

In humid areas, controlled drainage has been identified as a potential water management method for managing both water quantity and quality affecting surface water bodies (Ayars et al., 2006). A study conducted in Wood County, Ohio from 1999-2003 to examine the hydrology, water quality, and crop yield on Hoytville soils, showed 40% reduction of drainage flow volume in controlled drainage compared to conventional drainage (Norman, 2004).

It has been found that drainage water management strategies involving controlled drainage increased crop yield. In North Carolina, controlled drainage resulted in an average yield increase for corn by 11% and for soybean by 10% compared to conventional drainage in seven years of study period (Poole et al., 2013). In Indiana, drainage water management study showed increase in corn yield from 5.8% to 9.8% during a study period of four years (Delbecq et al., 2012). Similarly, in Ohio 1% to 19%

corn yield increase was observed from six out of nine observation plots, and 1% to 7% soybean yield increase was observed from seven out of 11 observations from drainage water management (Ghane et al., 2012). Further information about the effects of different management practices on field hydrology and crop yield is presented in Table 3.

Table 3. Literature review subsurface drainage impacts on hydrology and crop yield

Author	**Method/Experimental Design**	**Management Practices**	**Study Location**	**Study Period**	**Field/Plot Size**	**Soil Type**	**Impact on hydrology**	**Impact on Crop productivity**
(McLean and Schwab, 1982)	Paired field study	Corn, Soybean, Oats	Sandusky, Ohio	1976-1980	0.55 ha	Silty Clay Loam	Decrease in peak flow by 15.5% in growing season and 7.5% in non-growing season	N/A
(Madramootoo et al., 1995)	Field lysimeter and DRAINMOD	Soybean	Macdonald Campus, McGill University	1960-1990	-	Courval sandy loam	-	Soybean yield increased by 35% with weir setting of 0.6m under controlled drainage
Lalonde et al. (1996)	Field study: conventional drainage, and water table control at 0.25 m and 0.5 m above drain	Corn-soybean rotation, ridge tillage practice	Ontario, Canada	1992-1993	3.5 ha	Bainesville silty loam	Drainage flow decreased by 58-41% weir setting of 0.25m and 65-95% at weir setting of 0.50m.	N/A
Sands et al. (2008)	Plot scale study: Variation in drainage depth (120 cm and 90 cm) and drainage intensity (13 mmd^{-1} & 51 mmd^{-1})	Corn-soybean rotation (Nitrogen fertilizer practiced for corn only)	Wasec, Minnesota	2001-2005	12.1 ha	Webster silty clay loam	Drainage flow decreased by 20%	N/A
Drury et al. (2009)	Plot scale study: conventional drainage, controlled drainage, and controlled drainage-subirrigation	Corn-soybean rotation (Nitrogen fertilizer- N1 and N2 rates)	Ontario, Canada	1995-1998	1.5 ha	Brookston clay loam	N/A	Corn yield increased by 6% and soybean yield increased by 3%

Jaynes (2012)	Field study: control drainage and fertilizer application management	Corn-soybean rotation (Nitrogen fertilizer practiced for corn only)	Lafayette, Central Iowa	2006-2009	22 ha	Fine-loamy, mixed, superactive, mesic typic Endoaquolls	Drainage flow decreased by 21%	Soybean yield increased by 8%
(Cooke and Verma, 2012)	Paired field study with conventional and controlled drainage	Corn-soybean rotation and continuous corn	4 locations – Barry, Hume North and South, and Enfield, Illinois	2008-2010	85.01 ha	Drummer, Dana, Patton, Montgomery, Twomile, Orion, Haymod	Decrease in drainage flow by 35-96%	N/A
Helmers et al. (2012)	Plot experiments: two undrained plots, two conventional drainage plots, two shallow drainage plots, and two controlled drainage plots	Corn and soybean each year	Crawfordsville, Iowa	2007-2009	17 ha	Kalona, and Taintor Soil	Decrease in drainage flow by 37-46%	No Change
Drury et al. (2014)	Field study: conventional drainage and controlled drainage-subirrigation	Four treatments with winter wheat cover crop (CC), without cover crop (NCC), conventional drainage (UTD), Controlled drainage-subirrigation (CDS)	Ontario, Canada	1999-2005	1.6 ha	Brookston clay loam soil	Decrease in drainage flow by 9-28% in controlled drainage subirrigation condition	Increase in corn yield by 4-7% and soybean yield by 8-15%

3 METHODS AND MATERIALS

3.1 Study Area

A plot scale experimental site was established in 2013 for the drainage water management study at Southeast Research Farm located near Beresford in Clay County, South Dakota (Figure 8). The total area of the experimental site is 14.25 acre and has six plots which are divided in to three drained and three undrained plots. The plot layout is shown in Figure 9 and detail dimensions of the plots are shown in Figure 10. The size of each plot varies from 0.67 ha to 0.84 ha and subsurface drainage in all the plots was installed at a depth of 120 cm and spaced 24.4 m. The drained and undrained plots were further divided into Urea and Super U subplots. Urea and Super U subplots have control structures fitted with CTD sensors at the plot outlet for monitoring the drainage water flow. The CTD sensors are connected with data loggers and measure water depth in the control structure at 15 minute intervals. Two plots (plot 2 and plot 5) have each a rain gauge installed for measuring the precipitation amount. The water table depth in the field were monitored through observation wells installed in each plot fitted with Hobo depth sensor data loggers.

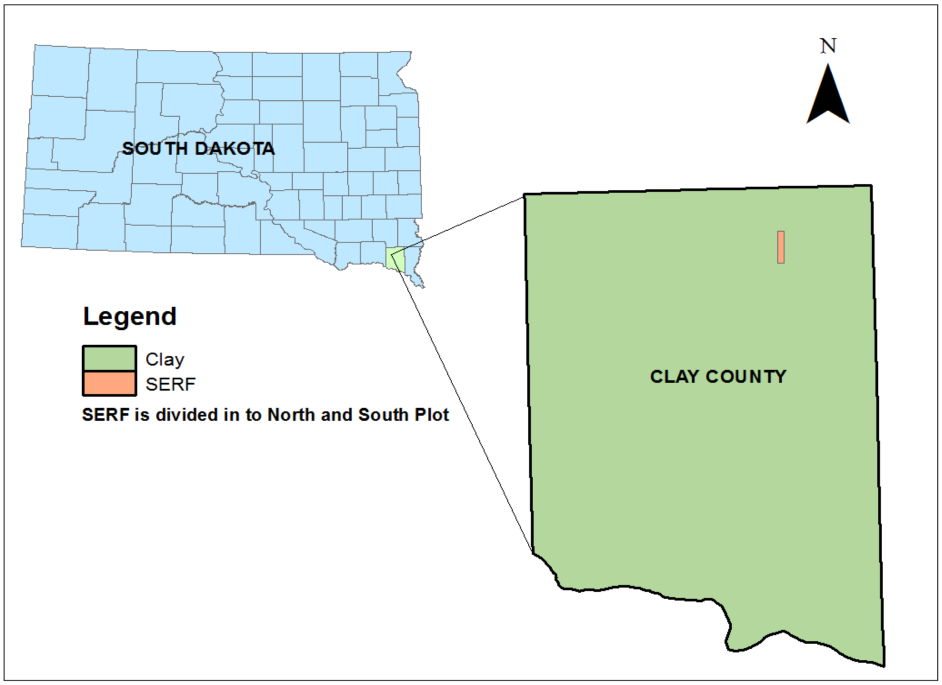


Figure 8. Southeast Research Farm (SERF), Clay County, South Dakota.

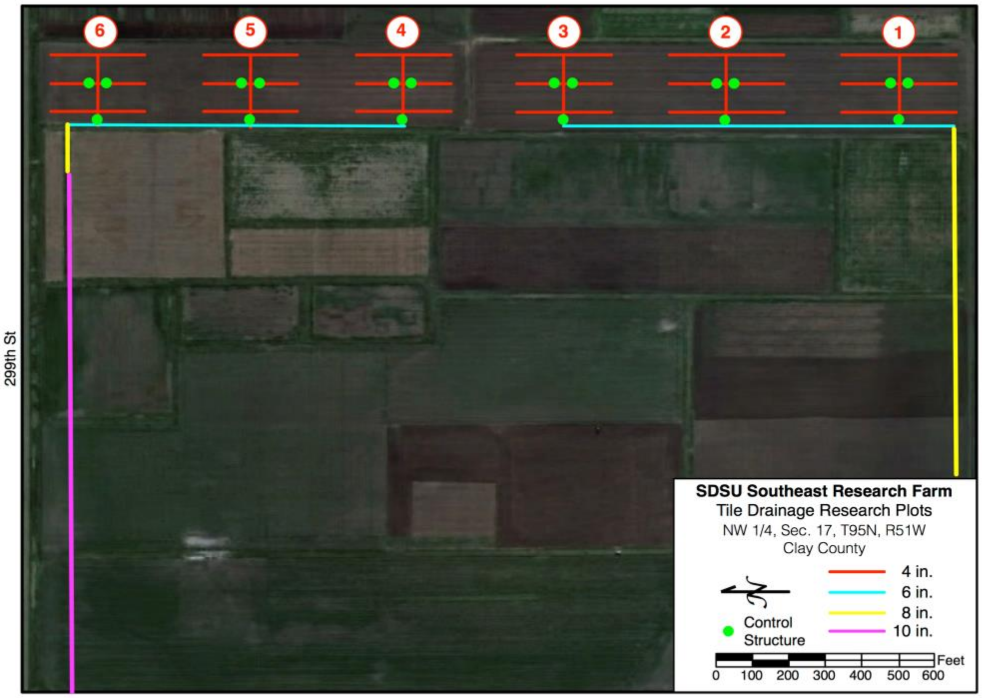


Figure 9. Plot layout and drainage design at SERF, Clay County, South Dakota.

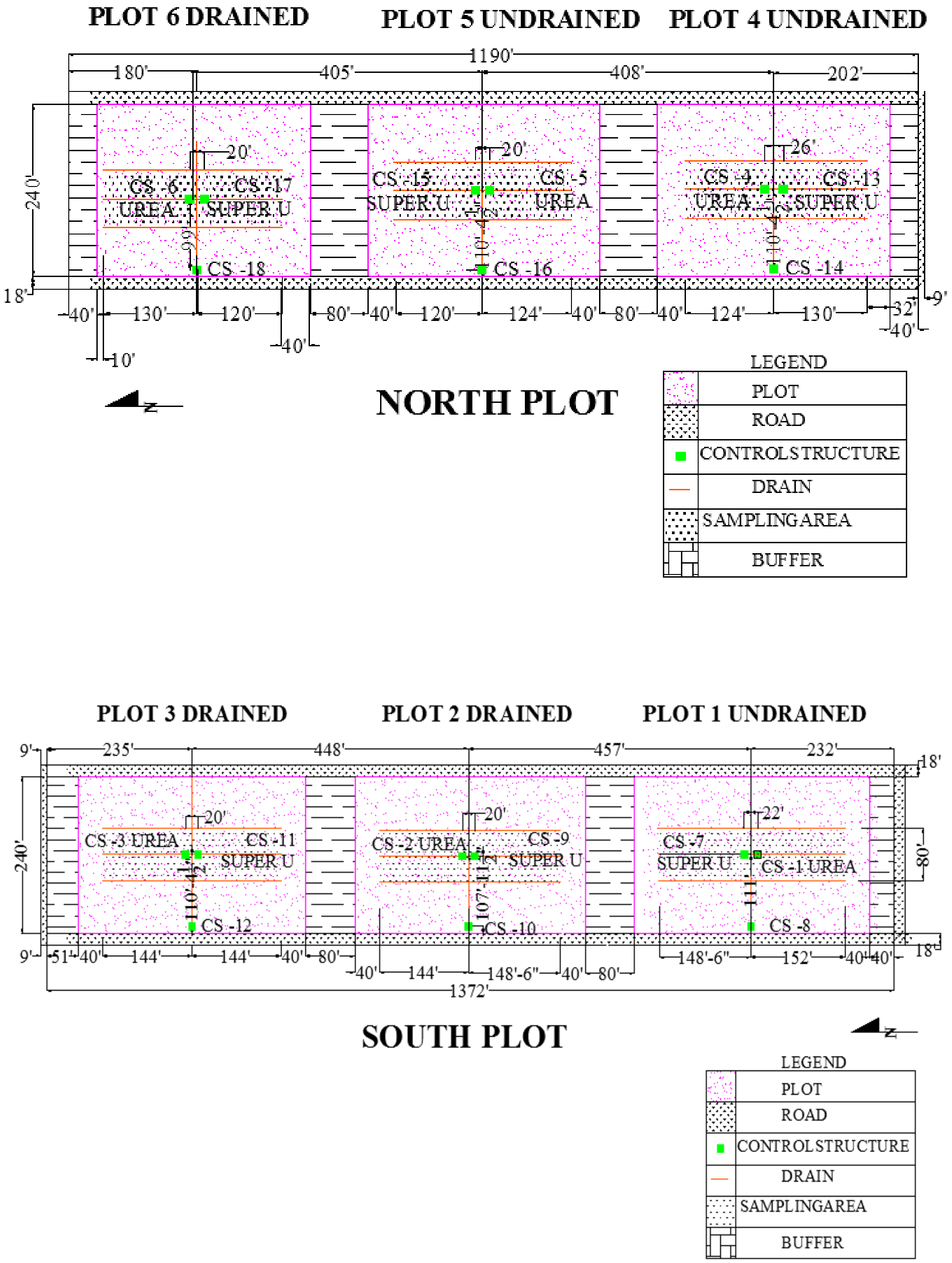


Figure 10. Drained and undrained plots dimensions (Karki, 2015).

3.1.1 Climate

The climate at the study area can be categorized as dry subhumid and receives average annual precipitation of 642 mm. Of this total, about 480 mm or 75 percent of rainfall usually falls in April through September (NRCS, 2001) in eastern South Dakota. The site has average daily maximum and minimum temperature of 14.7 ^{0}C and 1.4 ^{0}C respectively (SDOC, 2015). Also, this area receives average seasonal snowfall of 762 mm and sunshine about 75% of the time in summer and 57% of the time in winter (NRCS, 2001).

3.1.2 Soil Type

The soil type at the research site has been categorized as an EhA-Egan-Trent silty clay loam (NRCS, 2001) soil, which is composed of 40 to 60% Egan and similar soils, 24 to 40% Trent and similar soils. The subsoil soil group at the site consists of 8 to 16 inches dark to very dark grayish brown silty clay loam, 16-26 inches dark greyish brown to brown silty clay loam, 26-34 inches light yellowish brown silty clay loam, and 34 to 54 inches light yellowish brown, calcareous silty clay loam with redox concentrations and redox depletion in the lower 13 inches (NRCS, 2001).

3.1.3 Crop Management

The site has corn-soybean rotation management starting with soybean in 2013, followed by corn in 2014 in all the plots. No tillage was performed in the year 2013 and no fertilizer was applied during soybean crop period. In 2014, field was tilled up to depth of 10 cm–15 cm 13 days before corn planting. Urea treated with Agrotain at a rate of 3 quarts per ton and Super U fertilizer were surface broadcasted at a rate of 291 kg/ha 19 days before corn plantation.

3.2 DRAINMOD

To quantify the field water balance and crop yield response to varying drainage conditions and cropping systems, a drainage model called DRAINMOD was used. DRAINMOD is a field scale, process-based distributed model developed by Skaggs (1980) at North Carolina State University. The model was originally developed to quantify the hydrology of poorly drained soils or soils with shallow water table. The first version of the model was introduced in 1970s and has been through numerous modification (Skaggs et al., 2012b). The model was accepted in 1979 by the United State Department of Agriculture- Natural Resources Conservation Service (USDA-NRCS) as subsurface drainage system evaluation model and first version of DRAINMOD was installed on the USDA mainframe computer in 1982 located in Washington, DC (Skaggs et al., 2012b).

DRAINMOD model employs a simple water balance approach and computes water balance on the soil surface and in the soil profile having a unit surface area extended from ground surface to the impermeable layer and located in midway between two subsurface drains (Skaggs, 1980).

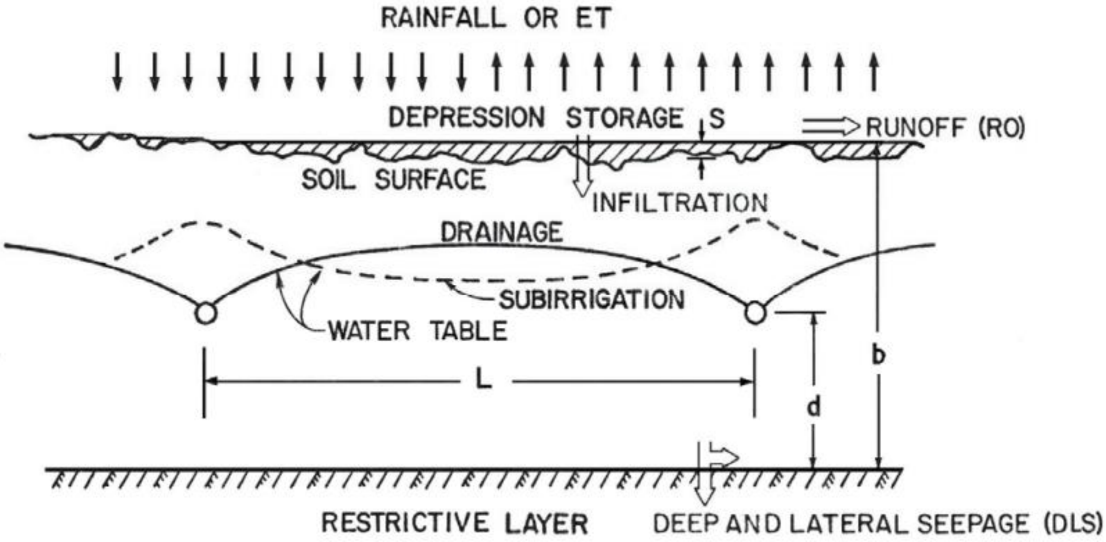


Figure 11. Major hydrologic components of DRAINMOD (Skaggs, 1978).

DRAINMOD quantifies various hydrological variables such as infiltration, subsurface drainage, surface runoff, water table depth, evapotranspiration, vertical and lateral seepage, and water free pore space in the soil profile on daily, monthly, and yearly basis (Skaggs, 1978). In addition, the model predicts annual relative crop yield (%) accounting for the effects of planting delay, wet-stress, drought-stress, and salinity on crop yield reduction. Input parameters required in the model are comprised of drainage system design, soil properties, crop parameters, and weather inputs. The drainage system inputs are mentioned in Table 4.

Table 4. Drainage design input parameters for DRAINMOD

Description of Parameters	**Value**
**Drain depth (cm)	120
Drain spacing (cm)	2440
Effective radius (cm)	0.51
Depth of impermeable layer from surface (cm)	200

Drainage coefficients (cm/day)	0.95
Initial depth to water table (cm)	30
Maximum surface storage (cm)	1
Kirkham's depth (cm)	50% of maximum storage
Drainage system	Conventional
**Note: In field, 1 ft. of board was set in control structure throughout the year and to account this in the model, a constant weir height of 1 ft. was taken into account for drain depth under conventional drainage configuration, resulting in a drain depth of 3 ft. (90 cm).	

DRAINMOD has inbuilt utility functions to create DRAINMOD readable input files, which includes weather file and soil file. Weather data used in this study were obtained from South Dakota Office of Climatology located at South Dakota State University and soil parameters were estimated using pedotransfer functions (Schaap et al., 2001). Soil utilities function was used to compute infiltration rate, water table, volume drained, upward flux, and soil water characteristics curve from input soil parameters. Crop potential evapotranspiration used in the model for different crops was computed from reference evapotranspiration and crop coefficient. The reference evapotranspiration was estimated using Ref. ET software (Allen, 2009), and crop coefficient was computed based on growing degree days (GDD). DRAINMOD also considers the effect of freezing and thawing, and therefore, freezing and thawing was considered in the model. The input parameters used for freezing and thawing are shown in Table 5.

Table 5. Soil temperature input parameters for DRAINMOD

Soil temperature Parameters	**Input value**
Computational depth function (a)	2.5 cm
Computational depth function (b)	1.21
Thermal conductivity function (a)	0.39

Thermal conductivity function (b)	1.33
Diurnal Phase lag of air temp	8 hrs.
Base temperature as boundary (^{0}C)	9.11
Rain/snow dividing temperature (^{0}C)	0
Snow melt base temperature (^{0}C)	1
Degree day coefficient (mm/day)	5
Critical ice content (cm^3/cm^3)	0.2

3.3 Creating DRAINMOD Input Files

3.3.1 Rainfall File

Rainfall records from January 1, 2004- December 31, 2015 obtained from SDSU weather station located in Beresford, SD were used to create DRAINMOD readable rainfall files. DRAINMOD has inbuilt utility functions to create DRAINMOD weather files (hourly or daily rainfall), temperature, and potential ET. The weather utility program has four parameters: input weather file, output file, weather variables, and units. As an input weather file, daily rainfall file for Beresford, SD was used. Daily rainfall input file contains three columns: first column of input file is the year, second column is the day of year, and the third column consists of rainfall amount (in inches, centimeter or millimeter) for that day. The utility program reads three columns of the daily rainfall file and then converts it into hourly rainfall based on the recommended number of rainfall distribution hours. In general, the recommended number of hours for daily rainfall distribution is either 4 hours or 6 hours to obtain hourly rainfall (Skaggs, 1990). In this research 4-hour distribution period was used. The starting of rainfall was set to 4 pm and end of rainfall was set to 8 pm, assuming that half of the rainfall occurs during day time

(4 pm to 6 pm) and half of the rainfall occurs during night time (6 pm to 8 pm) (Skaggs, 1990). DRAINMOD calculates ET from 6 am in the morning to 6 pm in the evening, and when rainfall occurs DRAINMOD does not consider ET during that rainfall event (Skaggs, 1990). If all the rainfall is distributed during the day time only, the model sets ET to zero for the day time and the predicted results may consequently be affected. After setting appropriate rainfall distribution hours, utility program was run to create DRAINMOD readable rainfall file (*.RAI).

3.3.2 Temperature File

To create DRAINMOD readable temperature file, temperature records from January 1, 2004-December 31, 2015 obtained from SDSU weather station located near Beresford, SD were used. Formatted temperature input file has four columns: first column as year, second column as ordinal date, third column as maximum temperature, and forth column as minimum temperature. The output temperature file was formatted as DRAINMOD readable file (*.TEMP).

3.3.3 Daily Crop Potential Evapotranspiration File

Daily crop potential evapotranspiration (PET) file creation involves various calculations before formatting it to DRAINMOD readable format. Crop PET can be computed using the appropriate model function or provided by the user. DRAINMOD has inbuilt PET calculation function that employs Thornthwaite (1948) method for computing PET based on the temperature and rainfall data. This method generally underpredicts PET during fall, winter, and spring months and overpredicts during summer months (Skaggs et al., 2012b). Thus, to avoid the uncertainty of under and overprediction, user defined crop PET was used for the simulations.

The first step of estimating crop PET involves estimation of evapotranspiration using Ref. ET: reference evapotranspiration calculation software, version 3.1 developed by Dr. Richard Allen at University of Idaho Research and Extension Center (Allen, 2009). The Ref. ET program provides standardized reference ET based on 15 most widely used methods for ET calculation in the United States. The standardized reference ET method adopted in this research is the American Society of Civil Engineers (ASCE) Penman-Monteith Standardized Form (Walter et al., 2000).To compute reference evapotranspiration (ET_r), weather data file consisting of date, rainfall, total energy (solar radiation), total energy (sun shine hours), temperature (minimum and maximum), relative humidity (minimum and maximum), average wind speed, obtained from the SERF weather station for the year 2004-2015 was used. In addition to the weather data file, weather station parameters presented in Table 6 for the SERF site were also required for ET_r calculation. After providing all input file and parameters, Ref.ET program was run to estimate daily ET_0.

Table 6. Input parameters for Reference ET as used in the Ref.ET program.

Parameters	**Values**	**Remarks**
Anemometer Height	3.66 meters	Standard reference value
Temperature/RH Height	1.35 meters	Standard reference value
Weather Station Elevation	388.92 meters	Referenced value
Weather Station Latitude	43.07 degrees	Measured value
Weather Station Longitude	96.93 degrees West	Measured value
Time Zone longitude	6 degrees West	Standard value
Default Day/Night Wind Ratio	2	Default value
Vegetation Height	0.12 meters	Standard value
Green Fetch of the Pan (A)	1000 meters	Standard value for unknown case

In the second step, daily crop coefficients for corn, soybean, and wheat were computed based on growing degree days (Hinkle et al., 1993; Lazzara and Rana, 2010; Nielsen and Hinkle, 1996). Growing degree days (GDD) or heat units is a method of assigning a heat value to each crop growing day. The GDD values are then added (cumulative GDD) to estimate the amount of total heat units that a crop can achieve during a growing season. The mathematical equation for estimating GDD (Derscheid and Lytle, 1977) is calculated as:

$$\text{GDD} = \frac{\text{Max.Temp.} + \text{Min.Temp}}{2} - \text{Base Temp.} \qquad (2)$$

Extreme temperature of 50 ^{0}C and 86 ^{0}C were used for GDD calculations. The equation required adjustment for extreme high (above 86 ^{0}C) and extreme low (below 50 ^{0}C). This implies that minimum temperatures below 50 ^{0}C are counted as 50 ^{0}C and maximum temperatures above 86 ^{0}C are counted as 86 ^{0}C (Derscheid and Lytle, 1977).

Crop coefficient (K_c) values reported by the High Plains Regional Climate Center (HPRCC) for different crop growth stages for corn, soybean, and wheat (Table 7) were used as references to compute daily crop coefficient based on Cumulative GDD. A time scale is then assigned for each crop growth stage with a corresponding cumulative GDD to compute daily crop coefficient for each crop, presented in Table 8 (Irmak and Irmak, 2008; Robertson, 1968).

Table 7. K_c values reported by HPRCC for different growth stages

Corn		**Soybean**		**Wheat**	
Growth Stage	**K_c**	**Growth Stage**	**K_c**	**Growth Stage**	**K_c**
2 Leaves	0.10	Cotyledon	0.10	Emergence	0.10
4 Leaves	0.18	First Node	0.20	Visual Crown	0.50

6 Leaves	0.35	Second Node	0.40	Leaf Elongation	0.90
8 Leaves	0.51	Third Node	0.60	Jointing	1.03
10 Leaves	0.69	Beginning Bloom	0.90	Boot	1.10
12 Leaves	0.88	Full Bloom	1.00	Heading	1.10
14 Leaves	1.01	Beginning Pod	1.10	Flowering	1.10
16 Leaves	1.10	Full Pod	1.10	Grain Fill	1.10
Silking	1.10	Beginning Seed	1.10	Stiff Dough	1.00
Blister	1.10	Beginning Maturity	0.90	Ripening	0.50
Dough	1.10	Full Maturity	0.20	Mature	0.10
Beginning Dent	1.10	Mature	0.10		
Full Dent	0.98				
Black Layer	0.60				
Full maturity	0.10				

Table 8. Cumulative GDD and corresponding estimated crop coefficient (K_c)

Corn		**Soybean**		**Wheat**	
CGDD	**K_c**	**CGDD**	**K_c**	**CGDD**	**K_c**
< 0	0.44	< 0	0.44	< 0	0.44
0-240	0.18	0-236	0.20	0-70	0.10
240-360	0.35	236-378	0.40	70-685	0.50
360-480	0.51	378-566	0.60	685-975	0.90
480-600	0.69	566-779	0.90	975-1175	1.10
600-720	0.88	779-968	1.00	1175-1675	1.00
720-840	1.01	968-1520	1.10	1675-1925	0.5
840-1920	1.10	1520-1702	0.9	<2000	0.10
1920-2160	0.98	1702-1851	0.2		
2160-2400	0.60	<2000	0.10		
<2450	0.1				

In the third step, the daily estimated crop coefficient was multiplied with daily reference ET for the period 2004-2015 to calculate crop potential ET (PET). Crop PET file having first column as Year, second column as ordinal date, and third column as PET was created. DRAINMOD weather utilities program was used to created DRAINMOD readable PET file. CGDD values less than 0 were considered as non-growing days and were assigned with crop coefficient values of 0.44 (Hay and Irmak, 2009).

3.3.4 Soil File

DRAINMOD model requires the following soil information- Soil water content versus pressure head (pf curve), lateral conductivity of each soil layer, Green and Ampt infiltration versus water table depth, upward flux versus water table depth, and volume drained versus water table depth. Model readable soil file was created using DRAINMOD inbuilt soil file utilities program. The soil input file used in the utilities program can be created using either pedotransfer functions (Schaap et al., 2001) or information of soil properties based on field (auger hole method) or lab method using HYPROP and WP4C (Rubio and Ferrer, 2012) measurements. The soil hydraulic properties for SERF site were estimated and lab measured using both pedotransfer and HYPROP method. For this research, soil data measured using HYPROP were used for further analysis. Further, saturated hydraulic conductivity values are considered sensitive parameters for DRAINMOD; therefore, values obtained with the HYPROP method were adjusted during model calibration and validation process. A description of the methods used for generating the soil file is explained below.

3.3.4.1 Rosetta Method

ROSETTA (Schaap et al., 2001) is a computer program for estimating water retention and soil hydraulic conductivity parameters. These pedotransfer functions employ five hierarchical sequence soil input data to compute saturated hydraulic conductivity based on Mualem (1976) pore size model which are given as-

a. Soil textural class
b. Sand, silt and clay percentages and bulk density
c. Sand, silt and clay percentages, bulk density, and a water retention point at 33 kPa
d. Sand, silt and clay percentages, bulk density, and water retention point points at 33kPa and 1500 kPa

The retention function used by ROSETTA is given as:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1+(\alpha h)^n]^{1-\frac{1}{n}}} \qquad (3)$$

where θ(h) is the water retention curve defining the water content, θ (cm^3/cm^3); θ_r and θ_s (cm^3/cm^3) are the residual and saturated water contents respectively; and α(1/cm) and n are the curve shape parameters. The equation (2) can be rewritten to compute relative saturation (S_e) as:

$$Se = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = [1 + (\alpha h)^n]^{1-\frac{1}{n}} \qquad (4)$$

The equation (4) is used in conjunction with the pore-size distribution model developed by Mualem (1976) to yield the Van Genuchten-Mualem model (Van Genuchten, 1980)

$$K(S_e) = K_0 S_e^L \left\{ 1 - \left[1 - S_e^{n/(n-1)} \right]^{1-1/n} \right\}^2 \qquad (5)$$

where K is the unsaturated hydraulic conductivity (cm/day), K_0 is the fitted matching point at saturation (cm/day) which may or may not equal to the saturated hydraulic conductivity, K_{sat}., and L is the empirical pore tortuosity/connectivity parameter (≈ 0.5). The soil parameters obtained from Rosetta are presented in Table 9 and Table 10.

Table 9 . Soil water characteristics curve generated using ROSETTA

Water Content (θ)	**Head (h)**
0.491	0
0.460	-25
0.430	-50
0.407	-75
0.388	-100
0.361	-150
0.341	-200
0.308	-330
0.283	-500
0.246	-1000
0.183	-5000
0.155	-15000

Table 10. Saturated soil hydraulic conductivity derived using ROSETTA

Depth (cm)	**K_{sat} (cm/hr)**
0-35	2.20
35-65	3.24
65-105	2.70

105-135	2.70
135-160	0.01

3.3.4.2 Lab Method-HYPROP

HYROP (Rubio and Ferrer, 2012)is a laboratory method for determining soil water retention curve and hydraulic conductivity. The HYPROP consists of a base, two precision mini-tensiometers, and standard 250 mL stainless steel soil sampling rings. The sampling rings were used to collect soil samples at three different soil depths, and two mini-tensiometer were used to measure water potential. The operation principle involves Schindler et al. (2010) evaporation method in which changes in water potential corresponds with changes in moisture content as the sample dries. Undisturbed soil samples were taken at different depth from field in the standardized soil sample ring as shown in Figure 12 and Figure 13. The soil samples were then brought to saturated condition before taking measurements by immersing them in water for at least 24 hours (Figure 14). Before starting the measurement, the base of the HYPROP and tensiometer were also saturated and preconditioned by de-airing and applying vacuum using deionized and degassed water. This is usually done with the help of syringes and vacuum refilling system (Figure 15). After de-airing and filling ionized water in base and tensiometer, saturated soil sample was fitted in the system (Figure 16 and Figure 17) and continuous measurements of pressure potential and weight were taken.

HYPROP-DES software was used for analyzing data obtained from HYPROP based on seven different inbuilt retention curve and conductivity curve models. HYPROP measured soil properties are presented in Table 11 and Table 12.

Figure 12. Undisturbed soil sample collection in the field at different soil depths.

Figure 13. Soil sampling rings for undisturbed soil sample collection.

Figure 14. Soil sample saturation process.

Figure 15. De-airing of HYPROP and tensiometer.

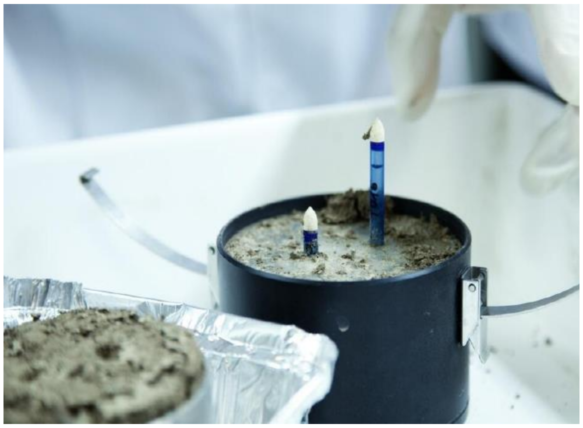


Figure 16. Tensiometer fitted with HYPROP base.

Figure 17. HYPROP base with tensiometer ready for reading.

Table 11. Soil water characteristics curve generated using HYPROP

Measured SWC	
Water Content (θ)	**Head (h)**
0.40	0
0.38	-26
0.36	-51
0.35	-74
0.33	-102
0.30	-155
0.28	-205
0.25	-310
0.21	-514
0.16	-1028
0.12	-2588
0.10	-5164
0.08	-10328
0.07	-15000

Table 12. Saturated soil hydraulic conductivity measured using HYPROP

Depth (cm)	**Value of K_{sat} (cm/hr)**
0-20	1.74
20-50	1.74
50-105	1.74
105-160	1.74

3.3.4.3 Saturated hydraulic conductivity

Saturated hydraulic conductivity is the most sensitive soil input parameter for DRAINMOD model; thus it is adjusted during model calibration and validation process. HYPROP measured saturated hydraulic conductivity was first used to run the model without calibration and later the hydraulic conductivity values were adjusted to calibrate the model.

Field observed drainage outflow was compared with model predicted drainage outflow for the year 2014 based on Nash-Sutcliffe Efficiency (NSE). For successful model calibration, it is required to have NSE values greater than 40%. Higher NSE value indicates better calibration, and therefore, to achieve better model calibration, simulation trials were conducted by changing saturated hydraulic conductivity input and comparing field observed drainage outflow with simulated drainage outflow. Calibrated saturated hydraulic conductivity input values are presented in Table 13 and was used for long-term simulations.

Table 13. Calibrated saturated hydraulic conductivity

Layer	Bottom Depth of Layer (cm)	Saturated Hydraulic Conductivity (cm/hr)
Layer-1	25	1.25
Layer-2	43	1.74
Layer-3	113	2.74
Layer-4	143	0.05

3.3.5 Crop File

DRAINMOD simulations can be run without defining a crop file, however, to predict potential crop yield it is essential to provide crop file. The crop file consists of rooting depths, excess soil water (SEW), and trafficability inputs. Additional parameters associated with the crop files include planting delays, excess and deficit soil water stress, and salinity stress. These parameters can be modified/adjusted based on the field measurements and site conditions. DRAINMOD model has reference crop input files already created for users for different regions of United States and can be used directly without modifying the reference crop files. The reference crop files used in this research were for corn, soybean, and wheat created for Minnesota region.

3.4 Model Calibration and Validation

Field observed drainage flow data from 2014 to 2015 collected from drained plot 6 at SERF at Beresford, SD were used for calibration and validation of the model. The model was also validated against water table data obtained from observation wells installed in the drained and undrained plots. The model was first calibrated in drained plot-6 by comparing the simulated drainage values with observed drainage values for the year 2014. For hydrologic model calibration and validation, saturated hydraulic conductivity was taken as sensitive parameter based on literature review, and adjustments were made to saturated hydraulic conductivity values. The calibrated model was then validated by comparing simulated drainage values with observed values for plot-6 for the year 2015. The model was again validated with respect to water table depth by comparing the simulated water table depth with observed water table depth for year 2014-2015 for plot-6.

3.5 Statistical Goodness of Fit

The statistical goodness of fit for model calibration and validation was measured using Nash-Sutcliffe efficiency (NSE), index of agreement (d), mean absolute error (MAE), and coefficient of determination (R^2). Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970) measures the fit between simulated and observed values and ranges from -∞ to 1. Mathematically, the Nash-Sutcliffe efficiency coefficient is expressed as:

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}\left(Q_{oi} - Q_{p}\right)^{2}}{\sum_{i=1}^{n}\left(Q_{oi} - \bar{Q}_{o}\right)^{2}} \qquad (6)$$

Index of agreement (Willmott, 1981) measures the degree of error of model predictions with values ranging from 0 to 1 where 0, indicates no agreement and 1 indicates perfect match. Mathematically, it is expressed as:

$$d = 1 - \frac{\sum_{i=1}^{n}\left(Q_{o} - Q_{p}\right)^{2}}{\sum_{i=1}^{n}\left(\left|Q_{pi} - \bar{Q}_{o}\right| + \left|Q_{oi} - \bar{Q}_{p}\right|\right)^{2}} \qquad (7)$$

Mean absolute error (MAE) defines the difference between the simulated and field observed values. Low MAE values indicates good match between the simulated and observed data. Mathematically, it is represented as-

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}\left|Q_p - Q_o\right| = \frac{1}{n}\sum_{i=1}^{n}|e_i| \qquad (8)$$

R^2 values show correlation between simulated and observed data and is expressed as-

$$r = \frac{\sum_{i=1}^{n}(Q_{oi}-\bar{Q}_o)(Q_{pi}-\bar{Q}_p)}{\sqrt{\sum_{i=1}^{n}(Q_{oi}-\bar{Q}_o)^2\ \sum_{i=1}^{n}(Q_{pi}-\bar{Q}_p)^2}} \qquad (9)$$

where, Q_o is the observed value, Q_p is the predicted value, $\bar{Q}_o$is the mean observed value, $\bar{Q}_p$ is the mean simulated value, Q_{oi} is the observed value for ith observation, $Q_{pi}$is the predicted value for ith observation, e_i is the average of absolute error, and n is the number of observation.

3.6 Long-term Simulation Scenarios

Long-term simulation scenarios for two drainage conditions (conventional and controlled) and one undrained condition were created to analyze the degree of variation in the field water balance under different crop practices (corn, soybean, and wheat), and crop yield response under those conditions. Long-term hydrology simulations from January 1, 2004- December 31, 2015 were performed for all simulation scenarios. The details of simulation scenarios are shown in Table 14.

Table 14. Long-term simulation scenarios

Simulation Scenarios	**Crop Management Scenarios**	**Drainage Scenarios**
Scenario-1	Continuous Corn	Conventional Drainage
Scenario-2	Continuous Corn	Controlled Drainage
Scenario-3	Continuous Corn	Undrained
Scenario-3	Corn-Soybean	Conventional Drainage
Scenario-4	Corn-Soybean	Controlled Drainage

Scenario-5	Corn-Soybean	Undrained
Scenario-6	Soybean-Corn	Conventional Drainage
Scenario-7	Soybean-Corn	Controlled Drainage
Scenario-8	Soybean-Corn	Undrained
Scenario-9	Corn-Wheat	Conventional Drainage
Scenario-10	Corn-Wheat	Controlled Drainage
Scenario-11	Corn-Wheat	Undrained
Scenario-12	Soybean-Wheat	Conventional Drainage
Scenario-13	Soybean-Wheat	Controlled Drainage
Scenario-14	Soybean-Wheat	Undrained
Scenario-15	Wheat-Corn	Conventional Drainage
Scenario-16	Wheat-Corn	Controlled Drainage
Scenario-17	Wheat-Corn	Undrained
Scenario-18	Wheat-Soybean	Conventional Drainage
Scenario-19	Wheat-Soybean	Controlled Drainage
Scenario-20	Wheat-Soybean	Undrained

3.7 Potential Crop Yield

DRAINMOD model predicts relative crop yield percentage from provided crop data. The relative crop yield percentage was then multiplied with potential yield capacity of a particular crop to obtain potential crop yield in kg/ha per year. No specific calibration was performed for crop yields. Corn and soybean yields were measured in the SERF field in the year 2013, 2014, and 2015. The potential yield for corn, soybean and wheat were taken from the literature (Luo et al., 2010; Wiersma et al., 2010; Youssef et al., 2005). The potential yield for corn and soybean were compared with field observed yield data, which was very close to the simulated. The field observed and potential crop yields are presented in Table 15.

Table 15. Observed crop yield and potential crop yield for corn, soybean and wheat used to estimate potential crop yield for the research site near Beresford, SD

Crops	Field Observed Crop Yield (Kg/ha)	Potential Crop Yield (Kg/ha)
Soybean	3380.6	3500, Youssef et al. (2005)
Wheat	-	5500, Wiersma et al. (2010)
Corn	13202.97	13000, Luo et al. (2010)

3.8 Subsurface Drainage Economics Analysis

Since the main purpose of installing subsurface drainage is to improve crop productivity of farmland, it is very essential to perform cost benefit analysis of the system. However, there is no standardized method for cost benefit analysis of subsurface drainage systems. Economic analysis was performed for three conditions: controlled drainage, conventional drainage, and undrained, and seven cropping systems, accounting for crop yield, cost of production, subsurface drainage installation and annual maintenance cost. The potential crop yields, obtained for corn, soybean, and wheat from field observed data and literature review, were used for estimating relative crop yields in kg/ha by multiplying potential yield with long-term relative crop yield percentage for each cropping systems. Production cost and crop selling price were adopted from various agency published databases (SDSU Extension, USDA, and Eastern South Dakota Grain Markets). Average corn price was assumed to be \$0.18/kg (\$4.5/bu), average soybean price was assumed to be \$0.42/kg (\$11.50/bu), and average wheat price was assumed to be \$0.24/kg (\$6.50/bu) based on the eastern South Dakota grain market values and SDSU

Extension estimated crop production cost (Davis, 2013; USDA, 2016). Drainage system installation cost was assumed to be \$3.95/m (\$1.2 per ft) (Edwards, 2013). Average annual profit was calculated by subtracting cost of production, subsurface drainage installation, and annual maintenance cost from average income per hectare.

The following equations were used for estimating drainage installation and maintenance cost:

$$\text{Drain length per ha} = \frac{10000\ \text{m}^2}{\text{drain spacing (m)}} \tag{10}$$

$$\text{Drainage installation cost} = \text{drainage cost}\left(\frac{\$}{\text{m}}\right) \times \ \text{drain length (m)} \tag{11}$$

$$\text{Drainage maintenance cost} = 25\%\ \text{of installation cost} \tag{12}$$

$$\text{Annual cost (ammortairezed @ 6\% interest rate for 30 years of drain life)}$$

$$= \frac{\text{I}(1+\text{I})^{\text{n}}}{(1+\text{I})^{\text{n}-1}(\text{Installation Cost}+\text{Maintenance Cost})} \tag{13}$$

where I is annual interest rate; n is total drain use life.

The following equation was used to compute net annual return from subsurface drainage-

$$\text{Net Annual return (\$/ha)} = \ \text{IC} - \text{CP} - \text{AC} \tag{14}$$

where IC is Income from crop production (\$/ha); CP is cost of production (\$/ha); AC is annual cost (\$/ha).

4 RESULTS

4.1 Calibration and Validation

The data required for calibration and validation have been discussed in the previous section on DRAINMOD in materials and methods. These includes data on drainage configuration, soil properties, weather, crop input, and site characteristics. The degree of agreement between predicted and measured values were quantified using four goodness-of-fit statistics; Nash-Sutcliffe efficiency coefficient, mean absolute error, r-squared and index of agreement. Model calibration was performed by comparing model predicted daily drainage volume with field observed daily drainage volume for year 2014. Agreement between model predicted and field observed results are plotted in Figure 18 and Figure 19 and results are summarized in Table 16. Results for predicted and field observed drainage volumes indicated good agreement, with Nash-Sutcliffe Efficiency (NSE) values of 0.727 and Mean Absolute Error values of 0.59 mm.

Model validation using the calibrated dataset was conducted by comparing model predicted and field measured daily drainage volume for year 2015 and daily water table depth for year 2014 and 2015. Results for predicted and measured drainage volume are plotted in Figure 20 and Figure 21. A summary of four statistical goodness-of-fit indicating model performance is presented in Table 17, Table 18, and Table 19. Agreement between model predicted and field observed drainage volume was good, with NSE values of 0.639 and MAE values of 0.79 mm. Likewise, agreement of predicted and field observed water table depths was excellent to very good, with NSE values of 0.96 and 0.70, and MAE values of 45.09 mm and 76.18 mm for year 2014 and 2015, respectively.

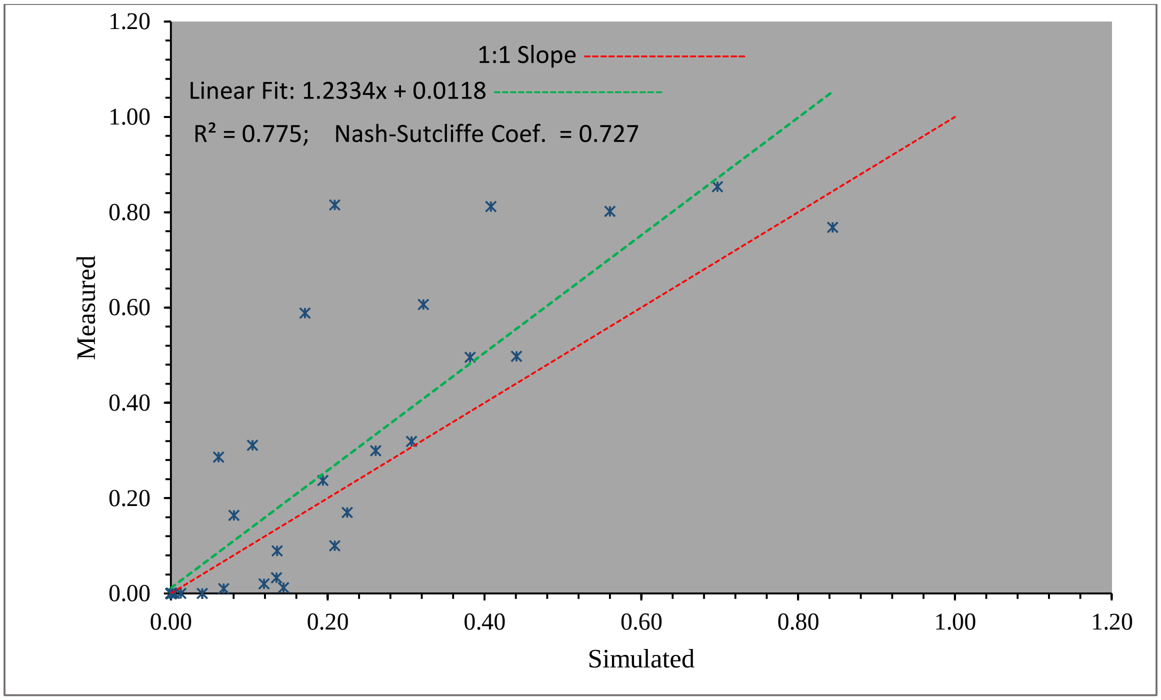


Figure 18. Model calibration using drainage outflow for year 2014 for plot 6.

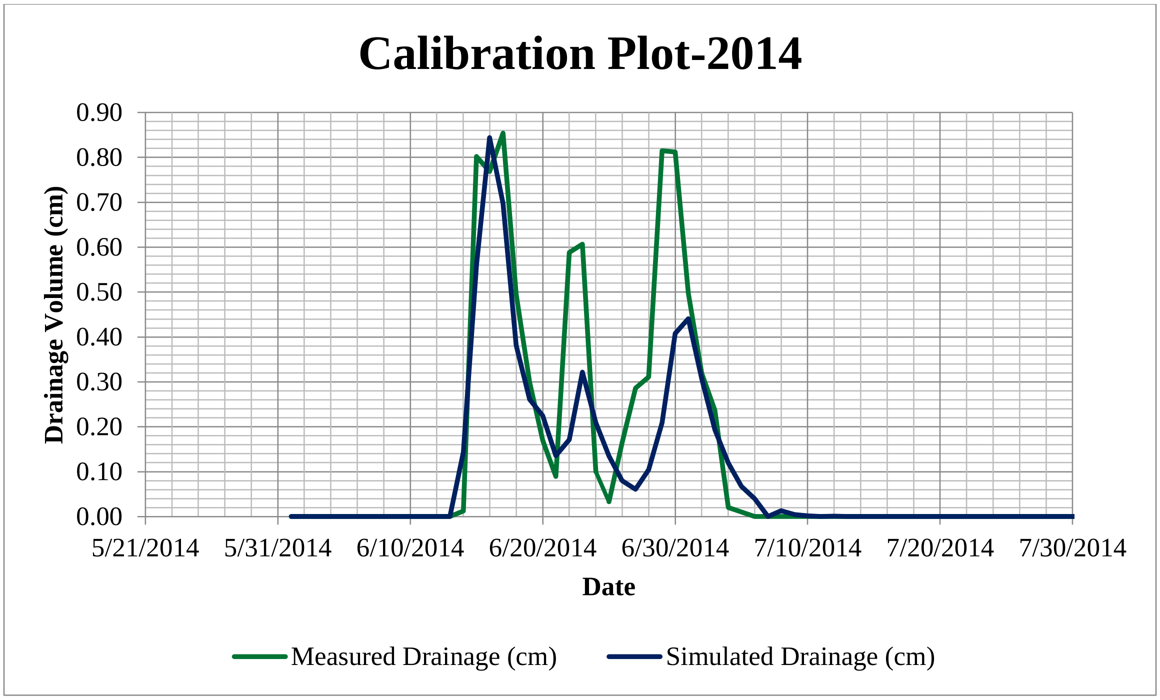


Figure 19. Time series plot for model calibration for year 2014.

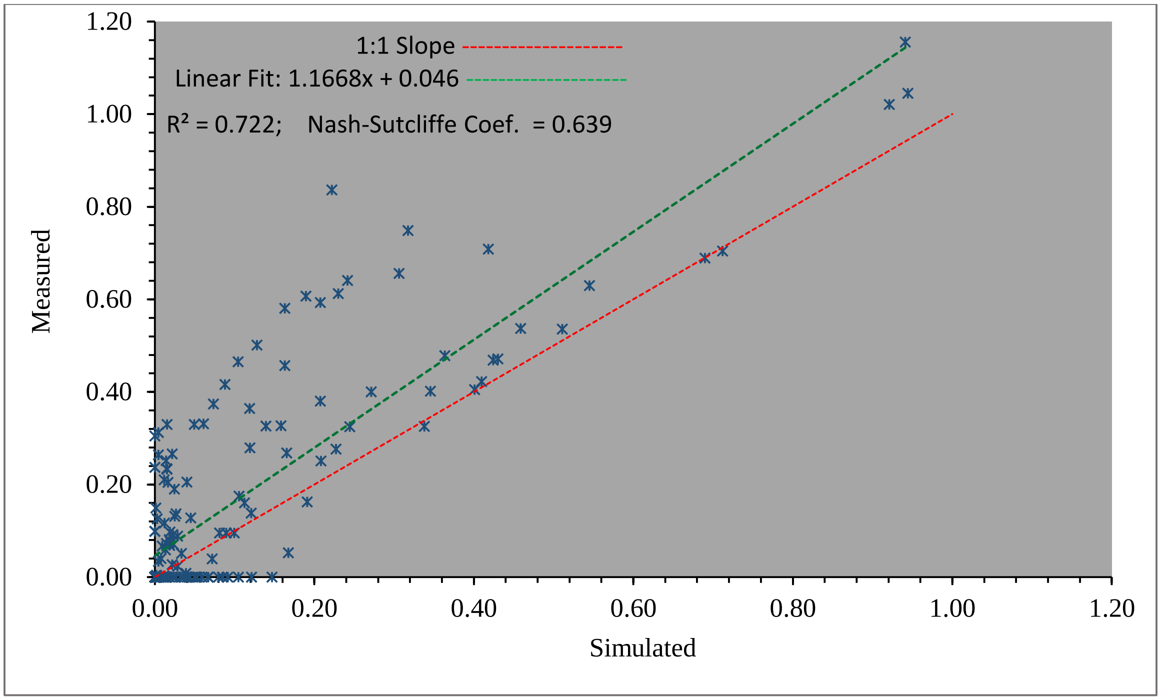


Figure 20. Model validation using drainage outflow for year 2015 for plot 6.

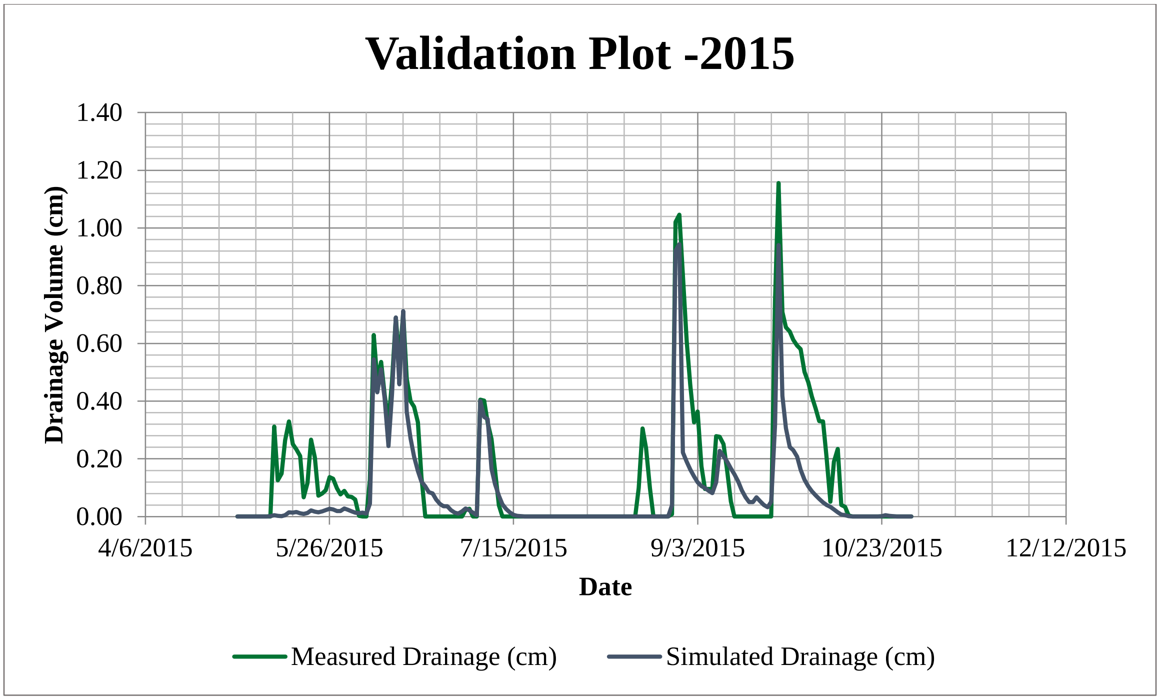


Figure 21. Time series plot for model validation for year 2015.

Table 16. Statistical summary for calibration using drainage volume for year 2014

Plot Numbers	Nash-Sutcliffe Efficiency (Calibration-2014)	R-Squared	Index of Agreement (d)	Mean Absolute Error (MAE) (mm)
Plot-6	0.727	0.775	0.903	0.59

Table 17. Statistical summary for validation using drainage volume for year 2015

Plot Numbers	Nash-Sutcliffe Efficiency (Validation-2015)	R-Squared	Index of Agreement (d)	Mean Absolute Error (MAE) (mm)
Plot-6	0.639	0.722	0.877	0.790

Table 18. Statistical summary for validation using water table depths for year 2014

Plot Numbers	Nash-Sutcliffe Efficiency (Validation 2014)	R-Squared	Index of Agreement (d)	Mean Absolute Error (MAE) (mm)
Plot-6	0.961	0.982	0.99	45.09

Table 19. Statistical summary for validation using water table depths for year 2015

Plot Numbers	Nash-Sutcliffe Efficiency (Validation 2015)	R-Squared	Index of Agreement (d)	Mean Absolute Error (MAE) (mm)
Plot-6	0.704	0.809	0.935	76.19

4.2 Long-Term Hydrology

4.2.1 Annual Water Balance

4.2.1.1 Subsurface drainage

Predicted 12-year (from 2004-2015) average annual subsurface drainage for different cropping practices under conventional and controlled drainage, and undrained drainage scenarios showed that controlled drainage substantially reduced drainage outflow for all cropping practices compared with conventional drainage. Average annual subsurface drainage for 12-year period for different cropping practices is shown in Figure 22.

Average annual drainage outflow was higher for wheat-corn crop rotation under conventional drainage condition, with a value of 107 mm. For the same cropping practice under controlled drainage condition, drainage outflow was 49 mm, which is more than 50% reduction in drainage volume. The lowest drainage outflow was observed in continuous corn cropping system under controlled drainage, with a value of 48 mm compared to all cropping practices under both controlled and conventional drainage conditions. For continuous corn under controlled drainage conditions, the drainage volume was 48 mm which is 28% less compared to drainage under conventional drainage condition. For soybean-corn and corn-soybean rotation, average annual drainage volume was similar with values of 77 mm and 74 mm under conventional drainage condition and 58 mm and 56 mm under controlled drainage condition, respectively. Thus, the simulation results indicated that controlled drainage has potential to reduce drainage outflow by more than 50% when compared with conventional drainage conditions. Other studies also found similar reduction in drainage volume, ranging from 20% to 95% in corn-soybean rotation under controlled drainage compared to conventional drainage (Cooke and Verma, 2012; Drury et al., 2014; Jaynes, 2012; Sands et al., 2008). Results for continuous corn, corn-soybean, and soybean-corn indicated lower drainage water yield under controlled and conventional drainage conditions compared with corn-wheat, wheat-corn, soybean-wheat, and wheat-soybean cropping practices. Adopting continuous corn, soybean-corn, wheat-corn, or corn-wheat rotation with controlled drainage can substantially reduce drainage outflow compared with conventional drainage.

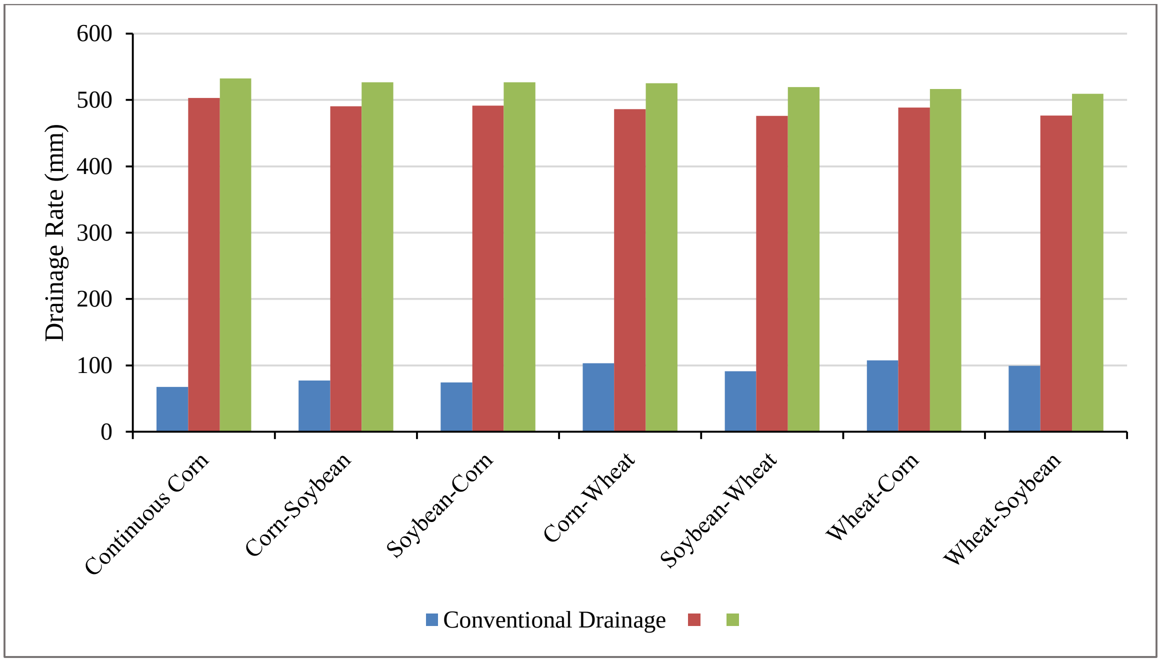


Figure 22. Average annual subsurface drainage for different cropping practices and drainage conditions.

4.2.1.2 Surface Runoff

Model simulation results showed that conventional drainage system considerably reduced surface runoff compared with controlled drainage and undrained conditions. Average annual surface runoff for 12-year period for different cropping practices under controlled and conventional drainage, and undrained conditions is plotted in Figure 23. Results for average annual surface runoff for 12-year period indicated low surface runoff for continuous corn and corn-soybean rotation under conventional drainage, with a value of 16 mm for both cropping practices. Under controlled drainage, the average annual surface runoff was 20 mm for both continuous corn and corn-soybean rotation, which is

25% higher compared with conventional drainage. Results indicated higher surface runoff for all cropping practices under undrained conditions with a maximum value of 82 mm for wheat-soybean rotation and a lowest value of 59 mm for continuous corn.

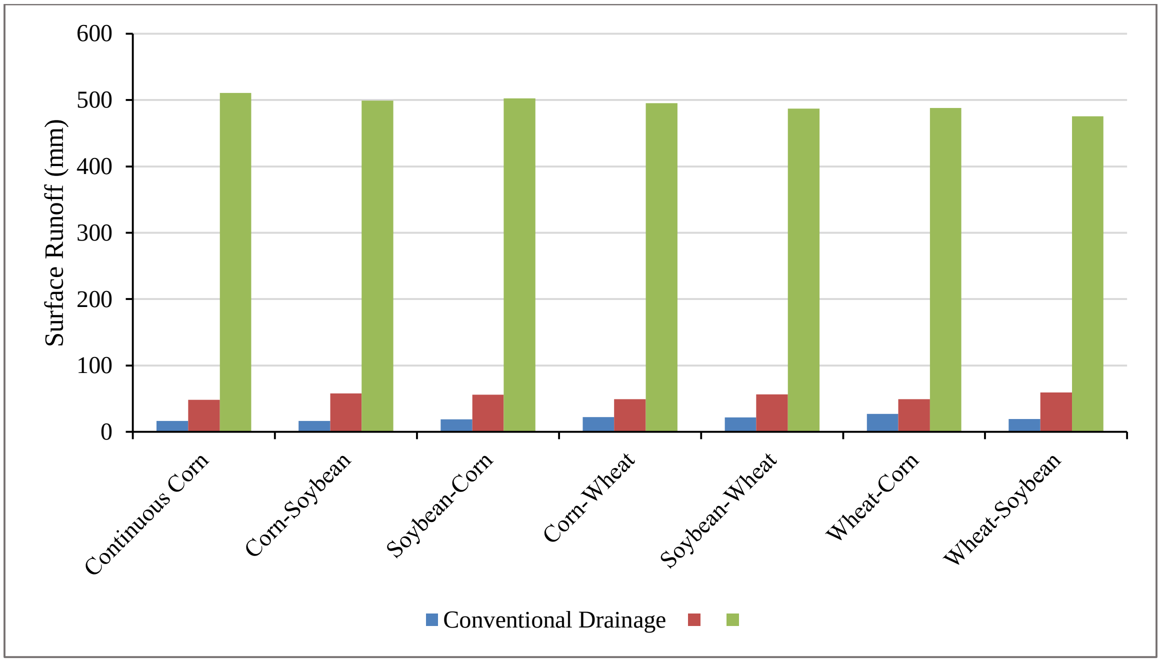


Figure 23. Average annual surface runoff for different cropping practices and drainage conditions.

4.2.1.3 Infiltration

Infiltration determines the soil's ability to permit water movement into and through the soil profile (Skaggs et al., 2006). Long-term simulation results showed that conventional drainage possesses more potential for higher infiltration rates compared to controlled and undrained conditions. Average annual infiltration rates for 12-year period for different cropping practices under conventional and controlled drainage and undrained conditions are plotted in Figure 24. Average annual infiltration results showed that continuous corn and soybean-corn have higher infiltration rates, with value of 575 mm for both cropping practices compared to all other cropping practices under conventional drainage, controlled drainage, and undrained conditions. Results indicated less variation in the infiltration rates between conventional drainage and controlled drainage conditions for all cropping practices. However, in all cases controlled drainage had lower infiltration rates compared to conventional drainage. Likewise, undrained conditions had less infiltration rates than the other two conditions for all cropping practices, with a maximum value of 532 mm for continuous corn and a minimum value of 475 mm for wheat-soybean.

The higher infiltration rate in conventional drainage indicated that drainage of excess water from the field provides more temporary storage to infiltrate water in the soil profile which in turn increases the infiltration rate. But in the case of controlled drainage, this temporary storage to infiltrate water gets reduced due to a shallower water table in the field at times of the year. Similarly, in undrained conditions water movement through soil profile gets restricted due to shallower saturated conditions, resulting in less water infiltration.

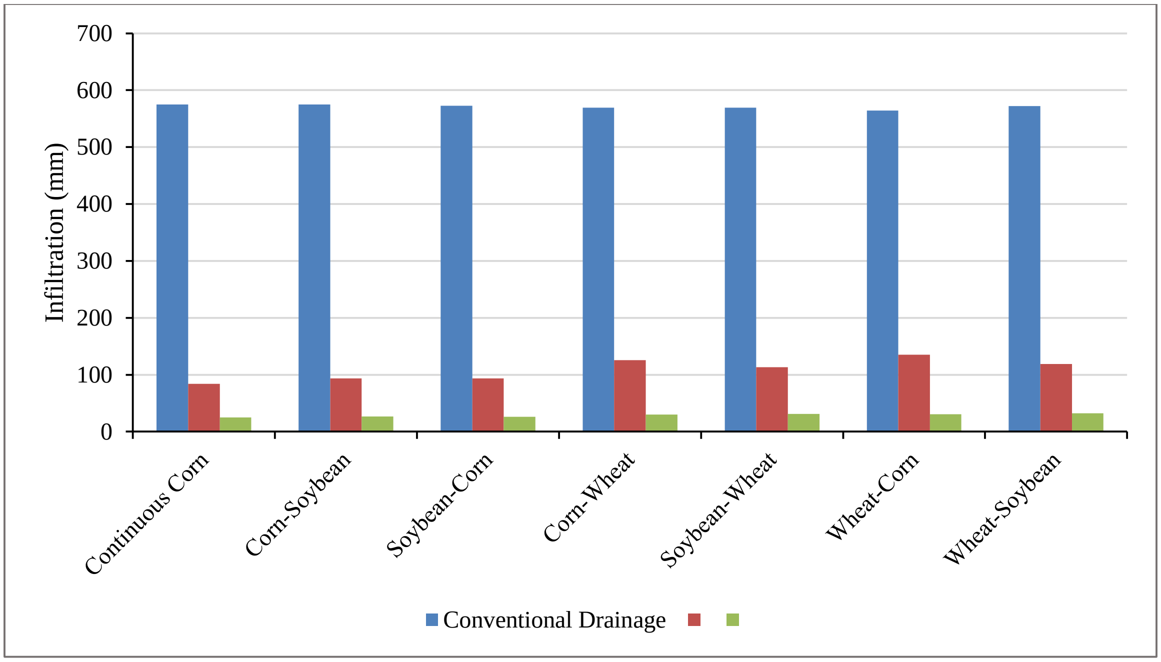


Figure 24. Average annual infiltration for different cropping practices and drainage conditions.

4.2.1.4 Evapotranspiration

Average annual evapotranspiration (ET) for 12-year period for different cropping practices under conventional and controlled drainage, and undrained conditions is plotted in Figure 25. Average annual evapotranspiration results indicated higher ET for undrained conditions compared with conventional drainage and controlled drainage. For controlled drainage, the maximum ET was observed in continuous corn cropping system with a value of 502 mm, and minimum ET was observed in soybean-wheat cropping system with a value of 475 mm. In undrained conditions, ET rate for continuous corn was 510 mm and 475 mm for wheat-soybean. Likewise, for conventional drainage the maximum ET was simulated for continuous corn with values of 490 mm and 453 mm and minimum ET was estimated in wheat-corn rotation with a value of 434 mm.

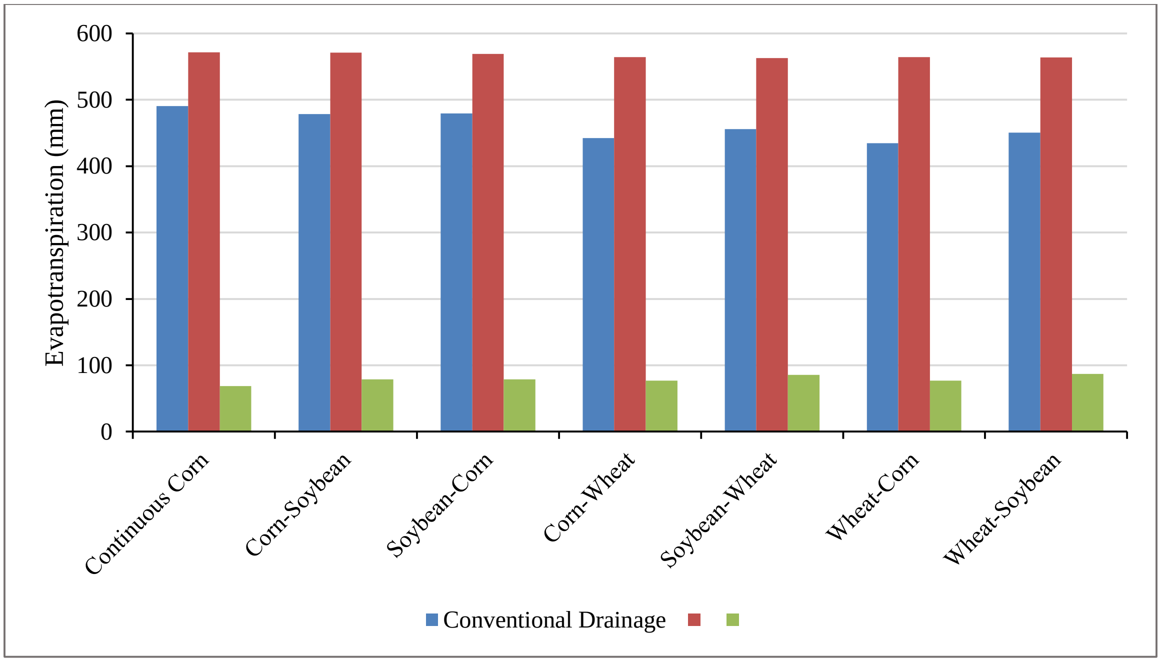


Figure 25. Average annual evapotranspiration for cropping practices and drainage conditions.

4.2.1.5 Vertical Seepage

Average annual vertical seepage for 12-year period for different cropping practices under conventional and controlled drainage and undrained conditions is plotted in Figure 26. Results indicated higher average annual vertical seepage for all cropping practices under undrained conditions and lowest vertical seepage for conventional drainage. The maximum seepage was predicted in wheat-soybean rotation under undrained conditions, with a value of 35 mm. Similarly, the minimum vertical seepage was predicted in continuous corn under conventional drainage system with a value of 22 mm.

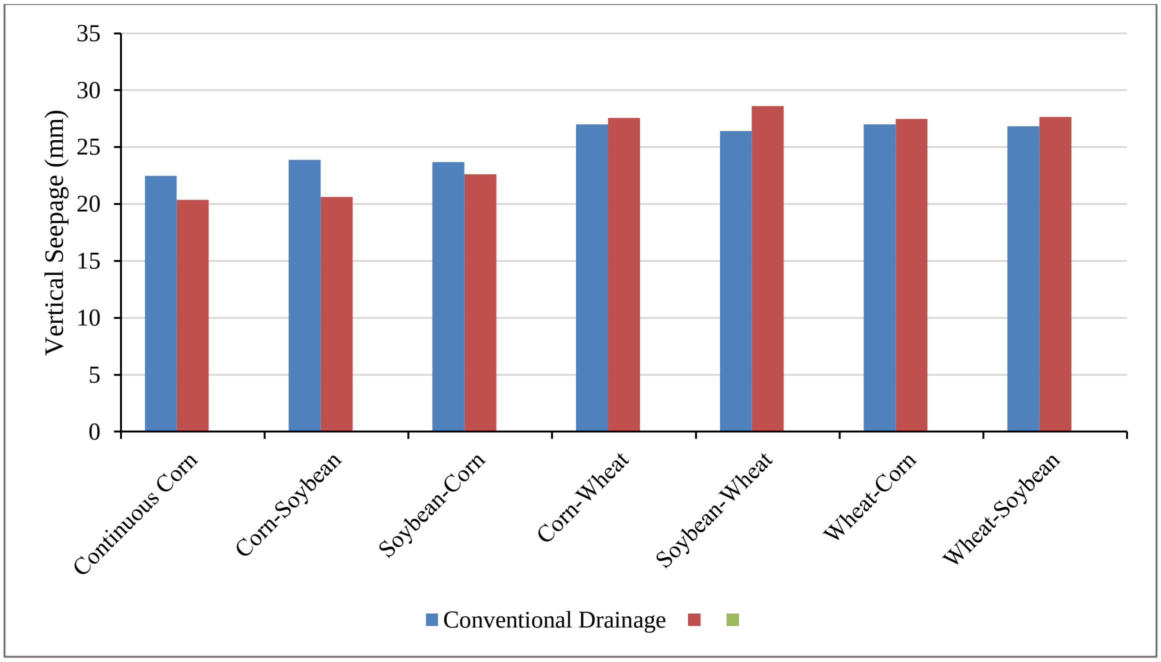


Figure 26. Average annual vertical seepage for different cropping practices and drainage conditions.

4.2.2 Water Balance Components as a Percentage of Precipitation

12-years average water balance components as a percentage of precipitation under conventional drainage, controlled drainage, and undrained condition is as shown in Figure 27, Figure 28, and Figure 29, respectively. In all three conditions, the major portion of precipitation is contributed in meeting evapotranspiration requirements which accounts for 70 -80% of precipitation. Under conventional drainage, subsurface drainage accounts 10-20% of precipitation and surface runoff accounts 2-4% of precipitation for different cropping practices. On the other hand, subsurface drainage only accounts 8-10% of precipitation whereas surface runoff accounts 10-15% of precipitation under controlled drainage for different cropping practices. In undrained conditions, surface runoff accounts 10-15% of precipitation. The lowest percentage of precipitation for three conditions is contributed to vertical seepage which accounts only 2-5% of precipitation.

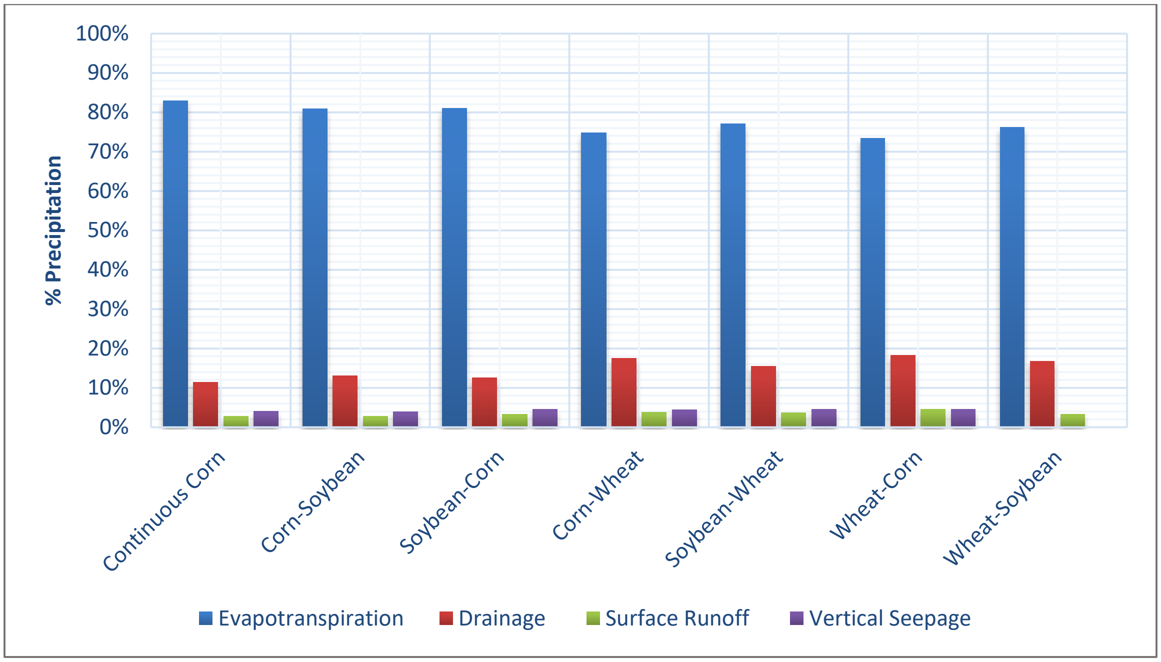


Figure 27. Water balance components under conventional drainage.

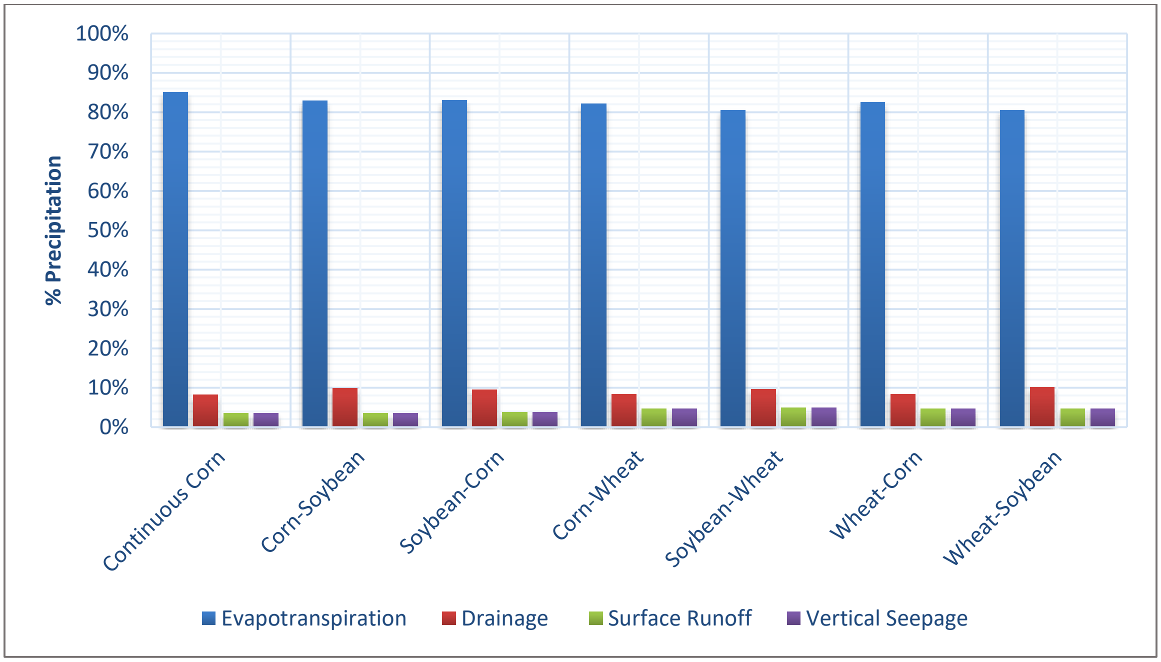


Figure 28. Water balance components under controlled drainage.

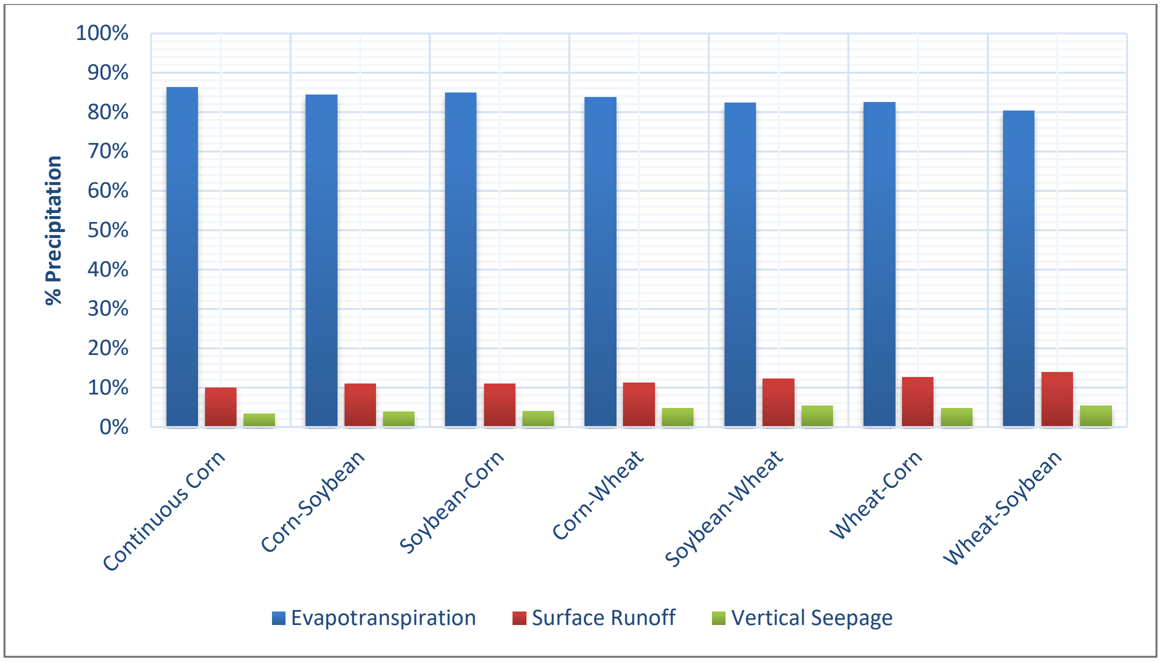


Figure 29. Water balance components under undrained condition.

4.2.3 Average Annual Water Yield

12-year average annual water yield (drainage and surface runoff) for different cropping practices under drained and undrained conditions is plotted in Figure 30. The results indicated higher water yield for wheat-corn under conventional drainage compared to all other cropping practices. The total value of water yield (drainage and runoff) for wheat-corn was 135.2 mm. Water yield for undrained condition for all cropping practices was minimum under undrained conditions as it does not account subsurface drainage volume and therefore, the water yield is only the result of surface runoff. Under controlled drainage, the maximum water yield was observed for wheat-soybean, with total water yield value of 87 mm. Subsurface drainage contributed less in water yield compared to surface runoff in controlled drainage. Whereas, subsurface drainage has higher contribution in water yield compared to surface runoff in conventional drainage.

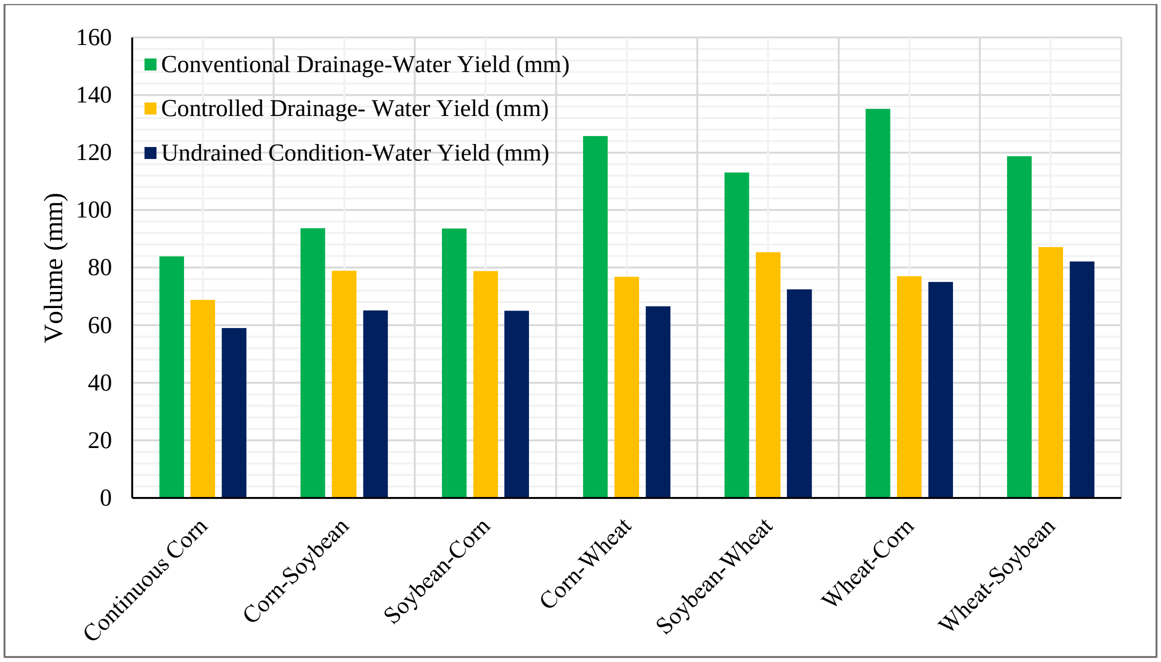


Figure 30. 12-year average annual water yield under drained and undrained conditions.

4.2.4 Monthly Water Balance

4.2.4.1 Continuous Corn

Average monthly precipitation, ET, drainage outflow, surface runoff, and vertical seepage for the 12-year period for continuous corn under conventional drainage, controlled drainage, and undrained conditions are plotted in Figure 31, Figure 32, and Figure 33, respectively. Average predicted drainage outflow for the month of May and June were predicted higher in conventional drainage compared to controlled drainage, with a peak value 30.3 mm in mid-June. Results indicated uniform drainage outflow from mid-May to mid-June under controlled drainage, with a maximum value of 22 mm. Since, controlled drainage provides control over drainage discharge by raising weir levels in the controlled structure, peak drainage discharge resulting from heavy rainfall events were minimized. During mid-September, some drainage outflow can be observed in both controlled and conventional drainage conditions. The average drainage outflow for mid-September was 2.4 mm and 0.6 mm for conventional and controlled drainage, respectively. Very less drainage outflow was predicted during month of July and no drainage during month of August because of high ET and less rainfall events.

ET was high from mid-May to mid-August, with peak values of 135.1 mm in undrained conditions, 129.6 mm in controlled drainage, and 127.3 mm in conventional drainage. The minimum values for ET were predicted from January to April and September to December which are generally considered a non-growing season in the research area, and have low temperature and abundant snowfall.

High surface runoff was predicted in undrained condition during the month of June when there was high precipitation. The average precipitation rate in June was predicted 113.7 mm and surface runoff in undrained field condition was 31.7 mm. In conventional drainage conditions, predicted surface runoff was 10.5 mm in June, whereas in controlled drainage surface runoff volume was predicted 11.8 mm.

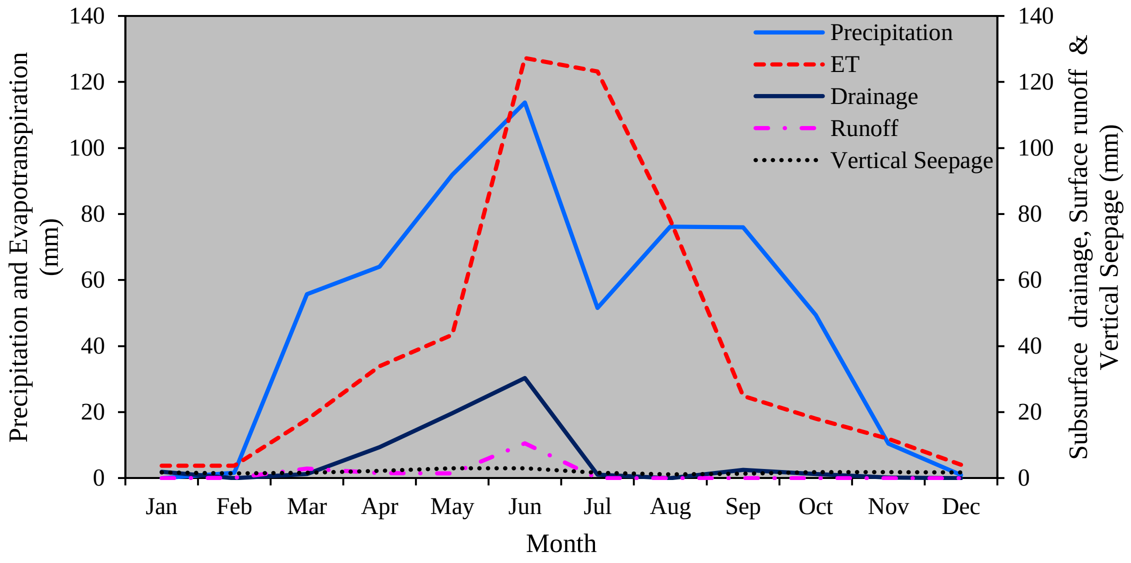


Figure 31. Monthly field water balance in continuous corn production under conventional drainage.

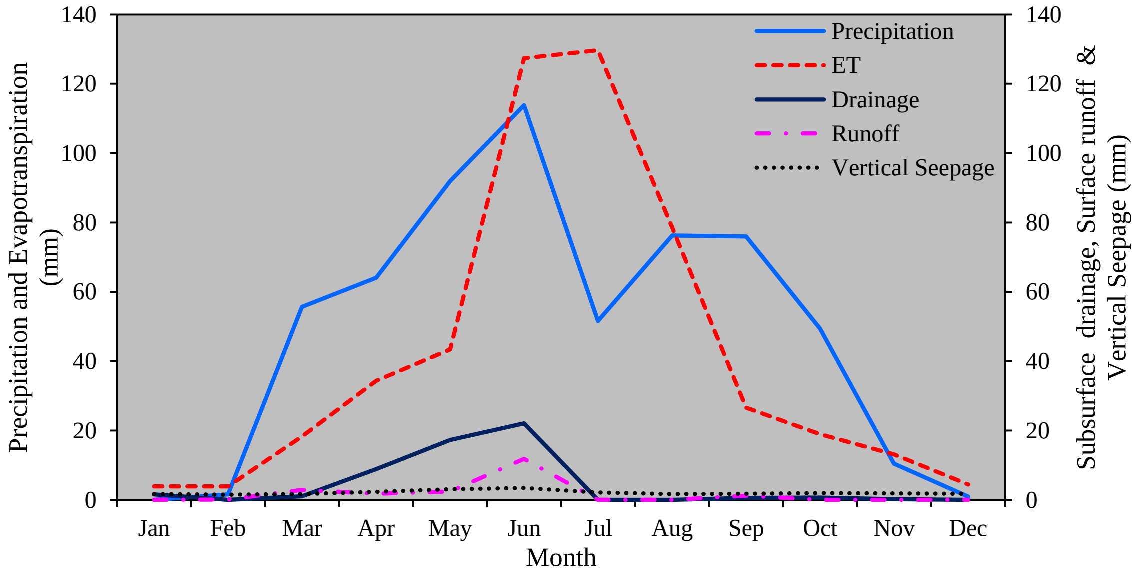


Figure 32. Monthly field water balance in continuous corn production under controlled drainage.

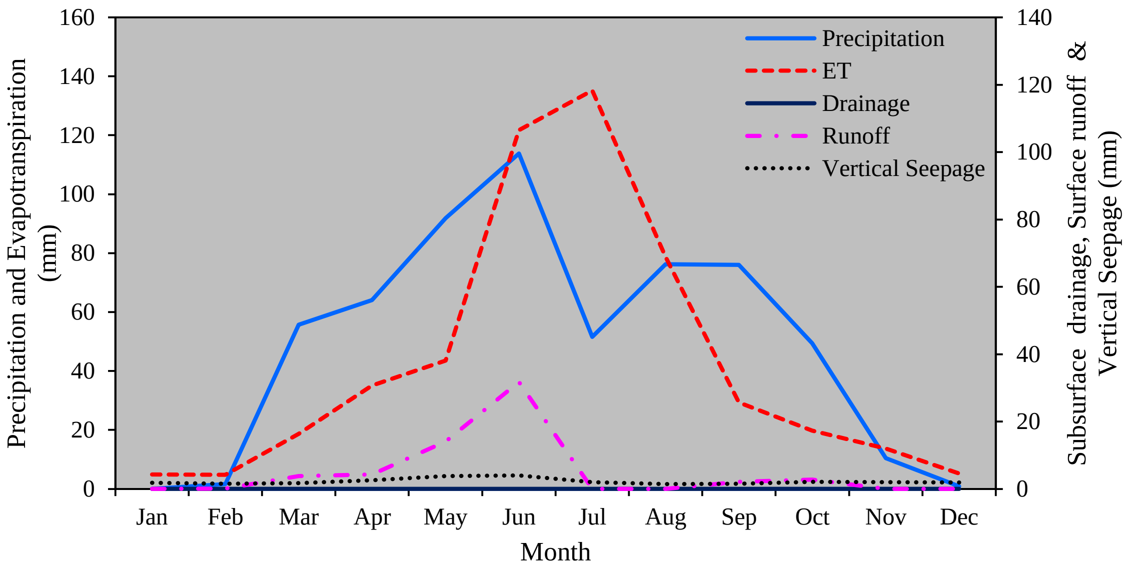


Figure 33. Monthly field water balance in continuous corn production under undrained condition.

4.2.4.2 Corn-Soybean Rotation

Average monthly ET, precipitation, subsurface drainage, surface runoff, and vertical seepage for the 12-year period for corn-soybean rotation under conventional, controlled, and undrained condition are as plotted in Figure 34, Figure 35, and Figure 36. From the plots below, it can be observed that majority of precipitation occurred during month of May to mid-July and again during August to September. Predicted results for monthly drainage outflow indicated peak discharge during May and July in conventional drainage. However, in controlled drainage the discharge was slight less but more uniform compared to conventional drainage. The maximum drainage outflow in conventional drainage in June was 30.8 mm. Similarly, in controlled drainage the maximum drainage outflow for June was 22.9 mm, which is less than 34% of conventional drainage outflow. No drainage outflow was predicted under controlled drainage and very minimal drainage under conventional drainage was predicted in July due to high ET and low precipitation value.

The maximum ET for conventional drainage, controlled drainage, and undrained condition was high during the month of July, with values of 119.3 mm, 121.0 mm, and 126.4 mm, respectively. Surface runoff was high in undrained condition from mid-May to mid-June, with a maximum value of 31.2 mm in June. In conventional drainage and controlled drainage, the maximum surface runoff was 10.5 mm and 11.7 mm, which is 66.3 % and 62.5% reduction in runoff volume compared to undrained condition. Similarly, no considerable difference in vertical seepage was found between conventional drainage, controlled drainage, and undrained conditions.

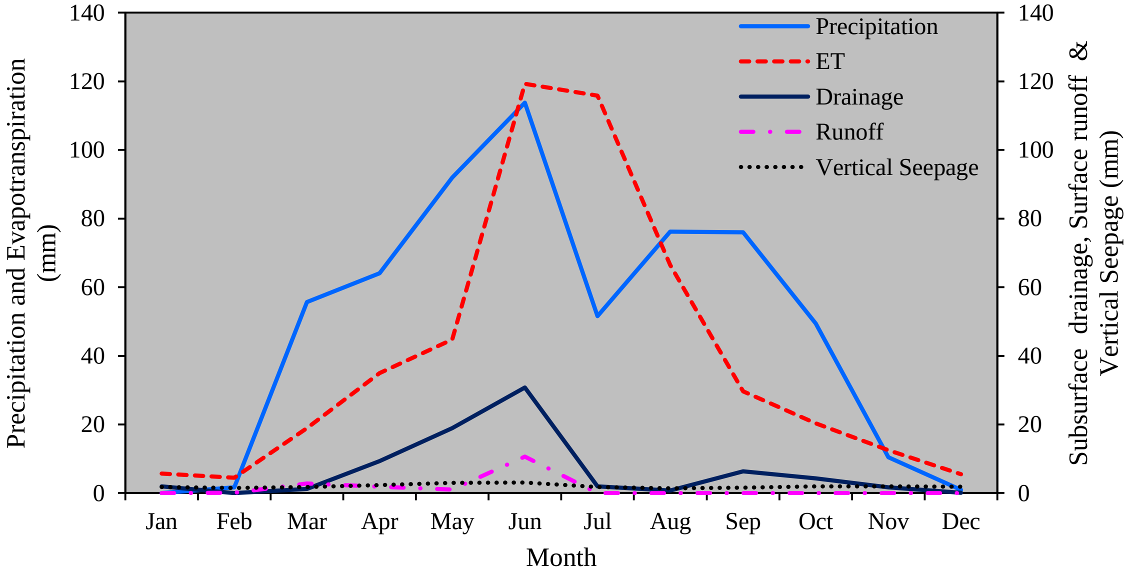


Figure 34. Monthly field water balance in corn-soybean production under conventional drainage.

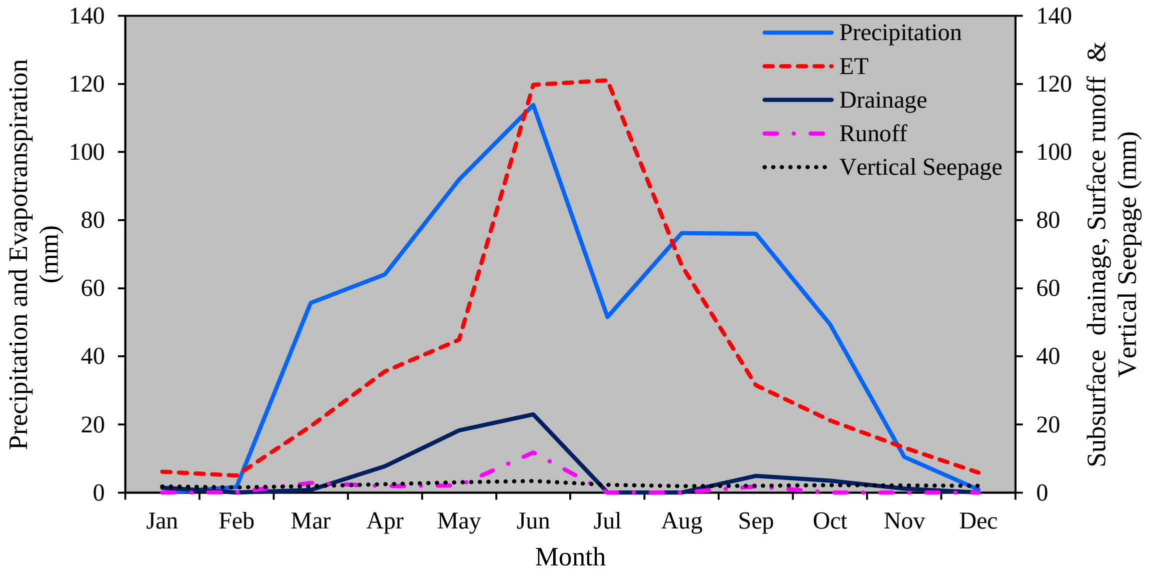


Figure 35. Monthly field water balance in corn-soybean production under controlled drainage.

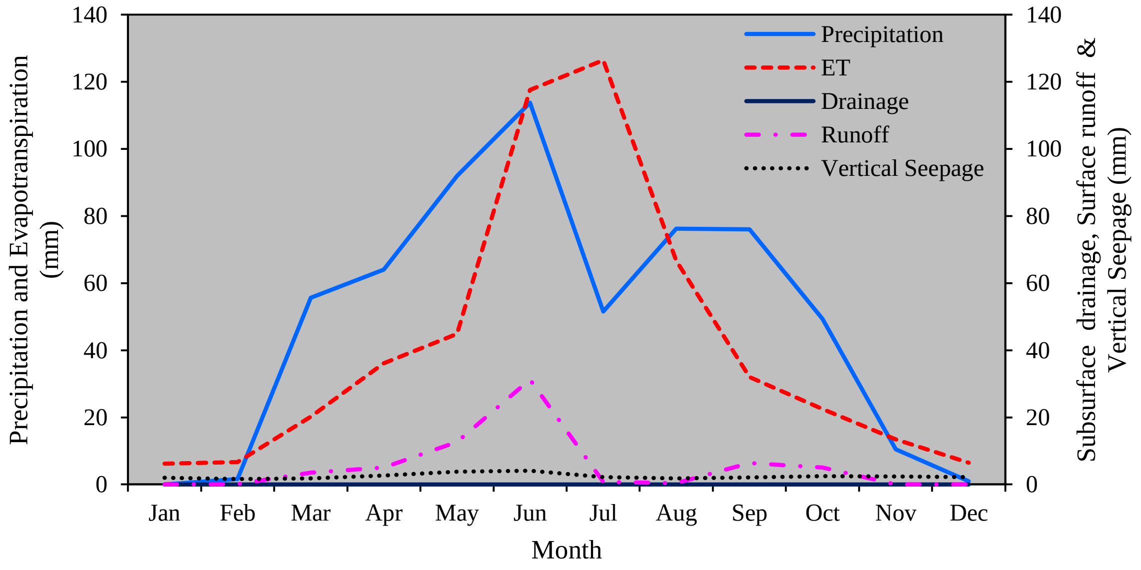


Figure 36. Monthly field water balance in corn-soybean production under undrained condition.

4.2.4.3 Soybean-Corn Rotation

Average monthly ET, precipitation, subsurface drainage, surface runoff, and vertical seepage for the 12-year period for soybean-corn rotation under conventional drainage, controlled drainage, and undrained conditions are plotted in Figure 37, Figure 38, and Figure 39. Monthly drainage outflow in conventional drainage was predicted high from mid-May to June, with a maximum value of 29.7 mm for June. Similarly, drainage outflow in controlled drainage for the month of June was found 21.8 mm, which is 35% reduction in drainage volume compared to conventional drainage volume. Drainage outflow was also observed in both drainage conditions during September to mid-October due to high precipitation and low ET. Drainage outflow for September to mid-October in conventional and controlled drainage was maximum in September with values of 6.4 mm and 5.8 mm, respectively.

Predicted average monthly surface runoff for undrained condition was high from May to June. Surface runoff value for May and June was 15.0 mm and 30.4 mm, respectively. For conventional and controlled drainage, similar runoff values were predicted. Also, no considerable difference in vertical seepage was predicted between conventional drainage, controlled drainage, and undrained conditions.

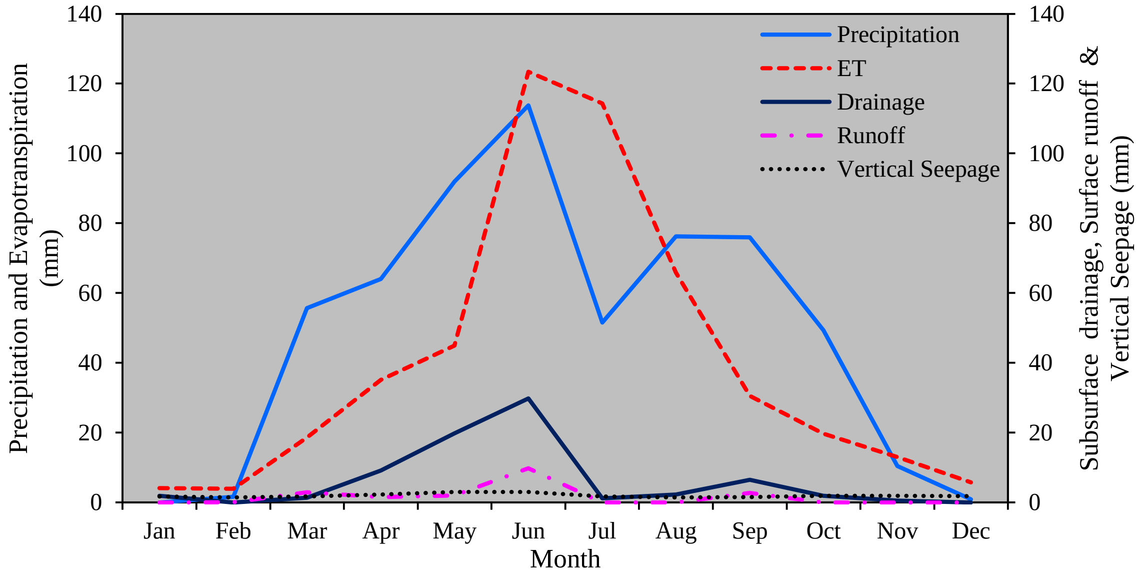


Figure 37. Monthly field water balance in soybean-corn production under conventional drainage.

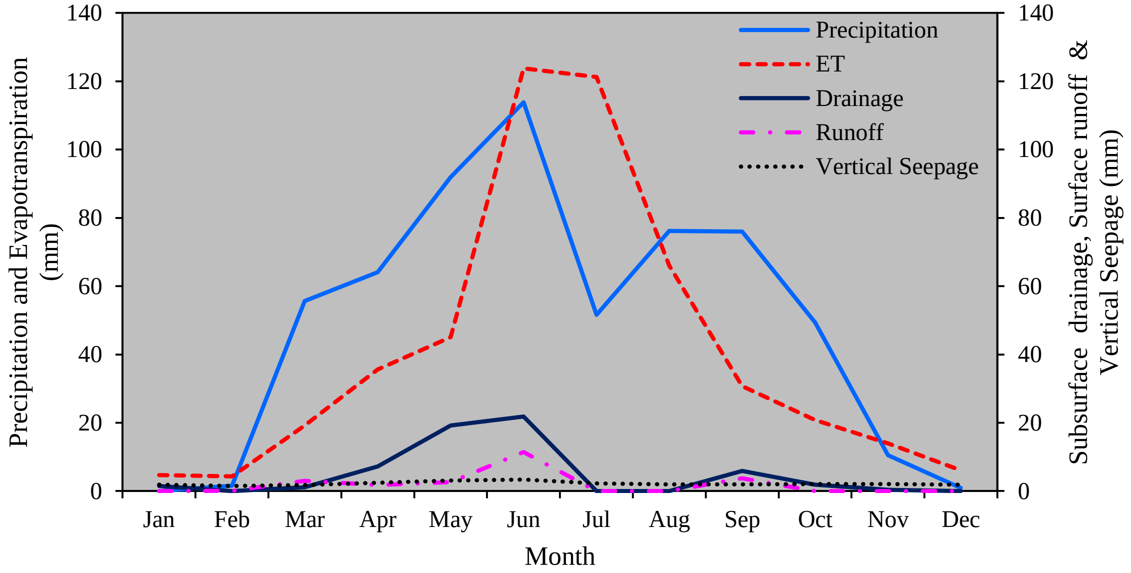


Figure 38. Monthly field water balance in soybean-corn production under controlled drainage.

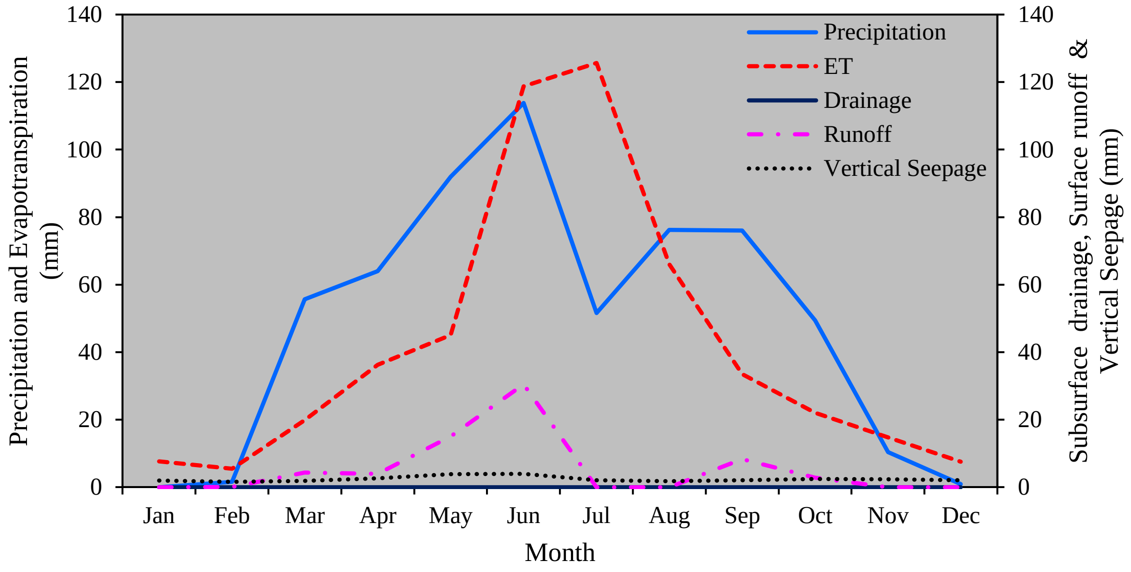


Figure 39. Monthly field water balance in soybean-corn production under undrained condition.

4.2.4.4 Corn-Wheat Rotation

Average monthly ET, precipitation, subsurface drainage, surface runoff, and vertical seepage for the 12-year period for corn-wheat rotation under conventional drainage, controlled drainage, and undrained conditions are plotted in Figure 40, Figure 41, and Figure 42. Predicted average monthly subsurface drainage results showed maximum outflow in conventional drainage from mid-May to June, with a value of 28.7 mm in June. Also, 9.7 mm and 19.1 mm of drainage outflow was predicted during the months of September and October. Results indicated that drainage outflow equals ET rate in the month of October in conventional drainage. Similarly, drainage outflow in controlled drainage was predicted from April to June, with a maximum value of 17.6 mm in June. No drainage outflow was observed in July due to high ET and low precipitation. Also, some drainage outflow was predicted for the months of September and October, with a maximum value of 5.9 mm in September. Drainage outflow in controlled drainage was predicted during September-October due to low ET.

Surface runoff was predicted slightly higher in controlled drainage compared to conventional drainage, with values of 11.9 mm and 9.6 mm in June, respectively. For the undrained condition, 28.9 mm of surface runoff was predicted for June which is 59 % and 66% greater compared to controlled drainage and conventional drainage, respectively. Also, model predicted some surface runoff for the month of October for undrained condition, with values of 6.5 mm which is around 60% greater compared to controlled and conventional drainage. Predicted results showed no considerable difference in vertical seepage rate between conventional drainage, controlled drainage, and undrained conditions for corn-wheat rotation.

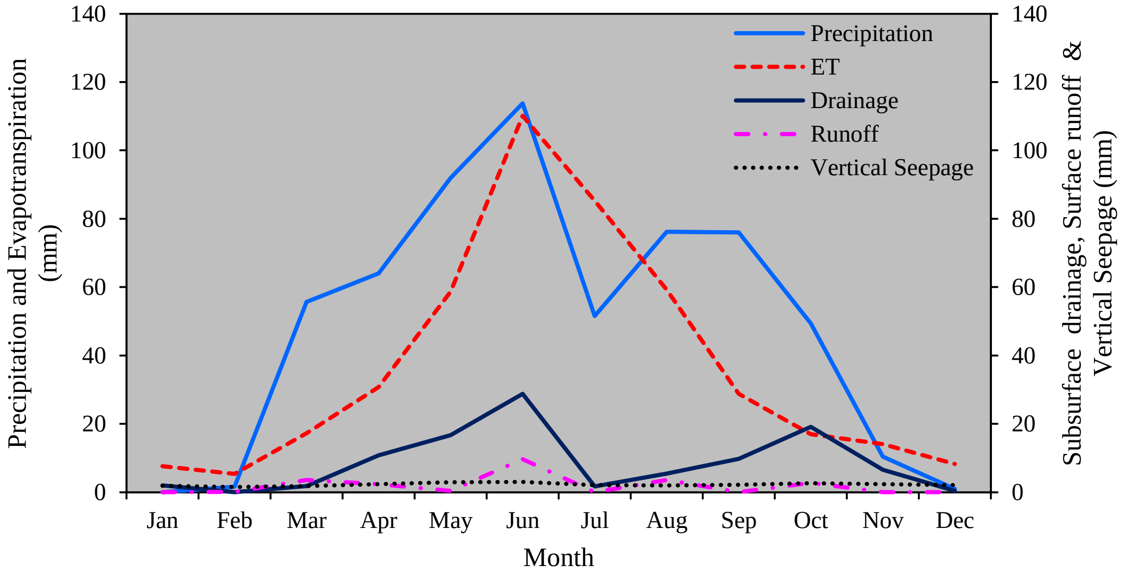


Figure 40. Monthly field water balance in corn-wheat production under conventional drainage.

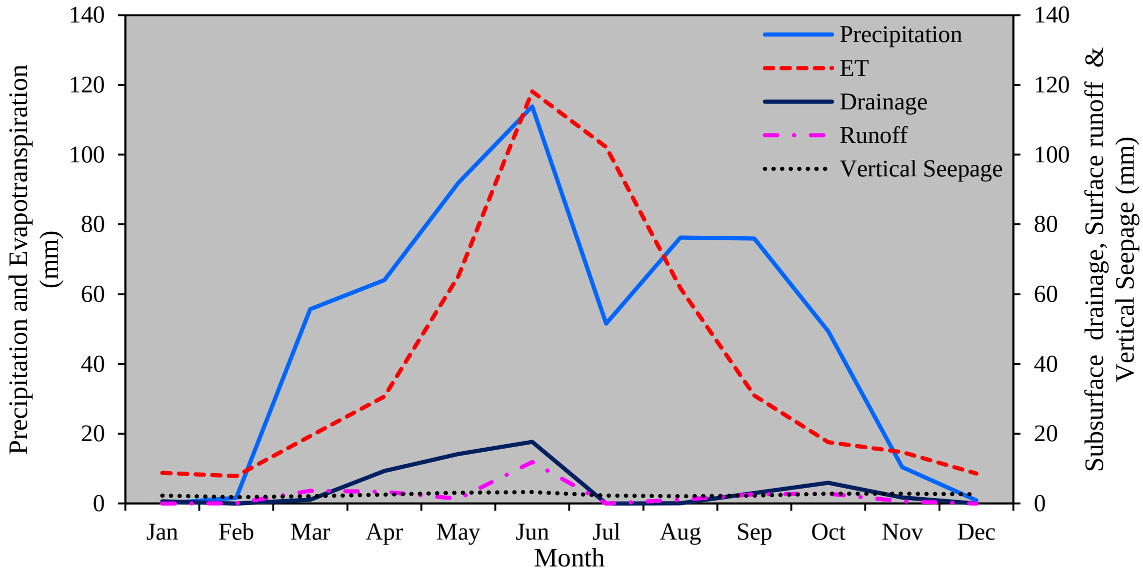


Figure 41. Monthly field water balance in corn-wheat production under controlled drainage.

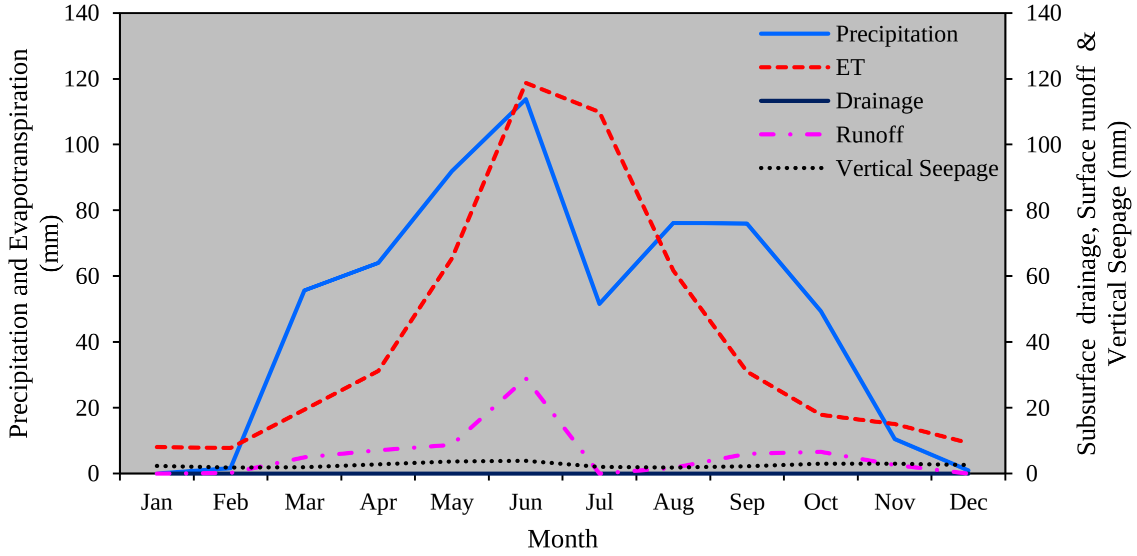


Figure 42. Monthly field water balance in corn-wheat production under undrained condition.

4.2.4.5 Soybean-Wheat Rotation

Average monthly ET, precipitation, subsurface drainage, surface runoff, and vertical seepage for the 12-year period for soybean-wheat rotation under conventional drainage, controlled drainage, and undrained conditions are as plotted in Figure 43, Figure 44, and Figure 45. Predicted average monthly subsurface drainage results showed high outflow in May, June, August, September, and October for both conventional and controlled drainage conditions.

In conventional drainage, maximum drainage outflow was predicted for June with a value 25.2 mm. Similarly, average monthly outflow for May, August, September, and October was 15.9 mm, 4.5 mm, 10.9 mm, and 12.7 mm, respectively. For July, drainage outflow was 1.2 mm. Likewise, drainage outflow for controlled drainage in June was 17.5 mm, which corresponds to 30% reduction in drainage volume compared to conventional drainage. The predicted drainage outflow for controlled drainage was maximum for September, with a value of 8.2 mm. Similarly, drainage outflow for May, August, and October was 16.9 mm, 1.5 mm, and 7.0 mm. For July, no drainage outflow was predicted under controlled drainage and very low outflow was predicted under conventional drainage.

Average monthly surface runoff in undrained condition for May, June, September, and October was predicted 8.3 mm, 28.3 mm, 12.2 mm, and 6.5 mm, respectively. In conventional drainage condition higher surface runoff values were predicted for June, with value of 9.4 mm and in controlled drainage condition higher surface runoff values were predicted for June, and September, with values of 10.9 mm, and 5.2 mm, respectively. In all three conditions, very small runoff value was predicted for the month of July due to high ET rate and low precipitation. Also, no considerable difference in vertical seepage was predicted between all three conditions.

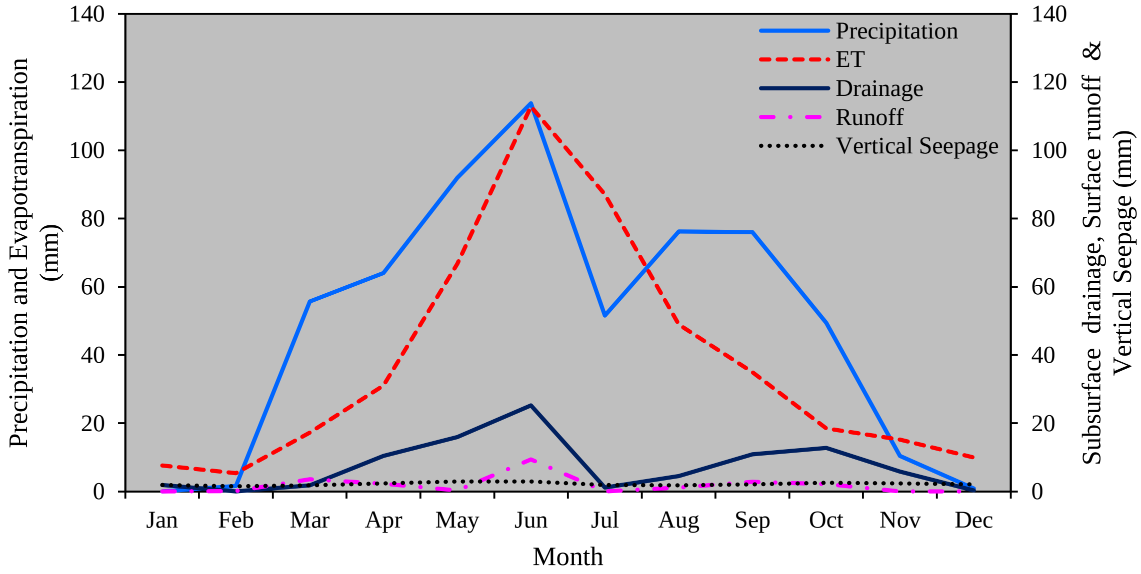


Figure 43. Monthly field water balance in soybean-wheat production under conventional drainage.

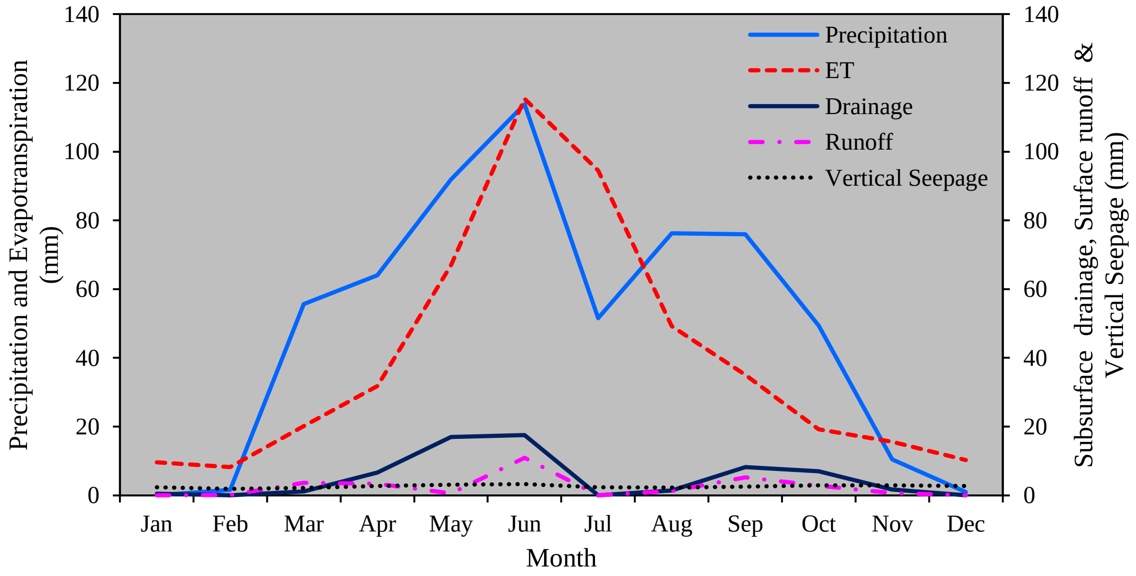


Figure 44. Monthly field water balance in soybean-wheat production under controlled drainage.

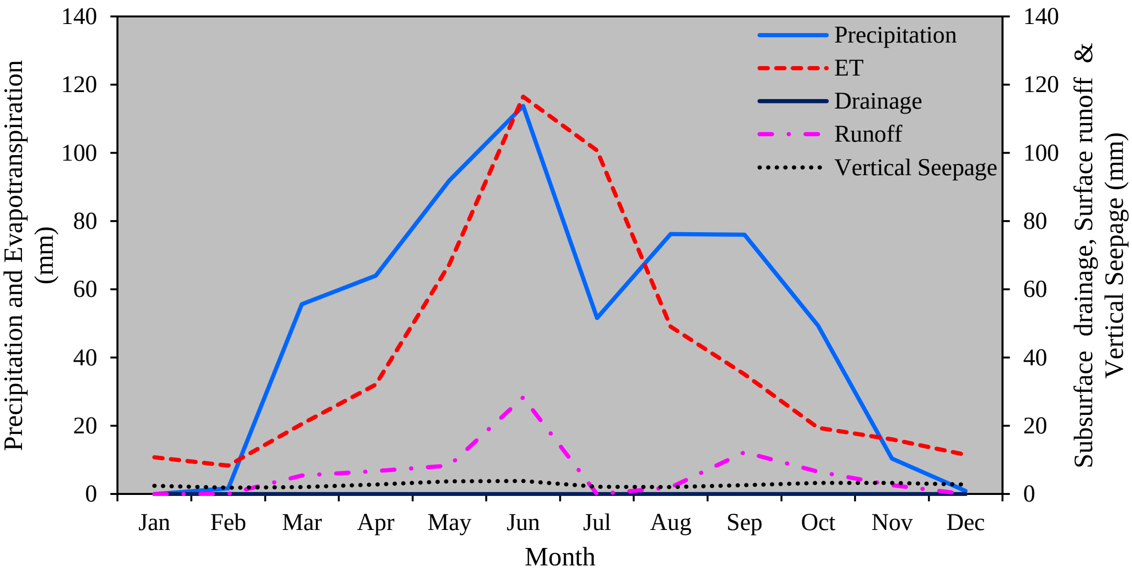


Figure 45. Monthly field water balance in soybean-wheat production under undrained condition.

4.2.4.6 Wheat-Corn Rotation

Average monthly ET, precipitation, subsurface drainage, surface runoff, and vertical seepage for the 12-year period for wheat-corn rotation under conventional drainage, controlled drainage, and undrained conditions are as plotted in Figure 46, Figure 47, and Figure 48. Average monthly subsurface drainage results under conventional drainage condition, drainage outflow was predicted higher in May, June, September, and October, with values of 20.9 mm, 29.9 mm, 16.7 mm, and 13.8 mm, respectively. Similarly, under controlled drainage condition outflow was predicted higher in May, June, and September with values of 17.9 mm, 19.1 mm, and 5.3 mm, respectively. Drainage outflow for July was very small in conventional drainage and no drainage under controlled drainage conditions due to high ET and low precipitation.

Average monthly surface runoff for undrained condition was high for May, June, and September with values of 14.4 mm, 27.9 mm, and 13.8 mm, respectively. In conventional and controlled drainage conditions, surface runoff rate was predicted higher in June and September, with values of 10.6 mm and 6.4 mm, respectively for conventional drainage, and 9.7 mm and 8.3 mm, respectively for controlled drainage. No considerable difference in vertical seepage value was predicted between three conditions.

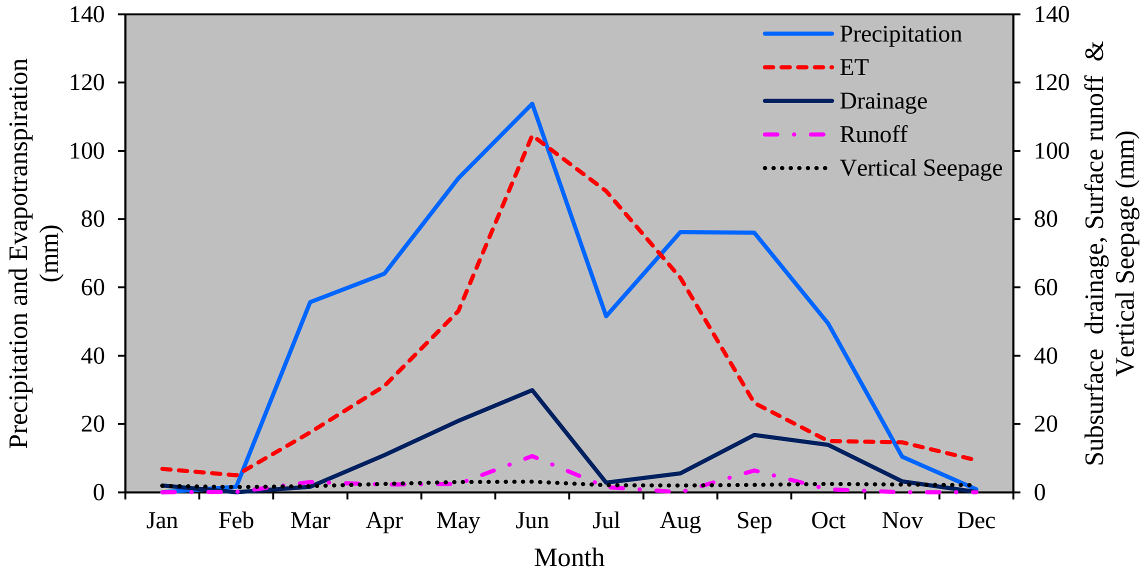


Figure 46. Monthly field water balance in wheat-corn production under conventional drainage.

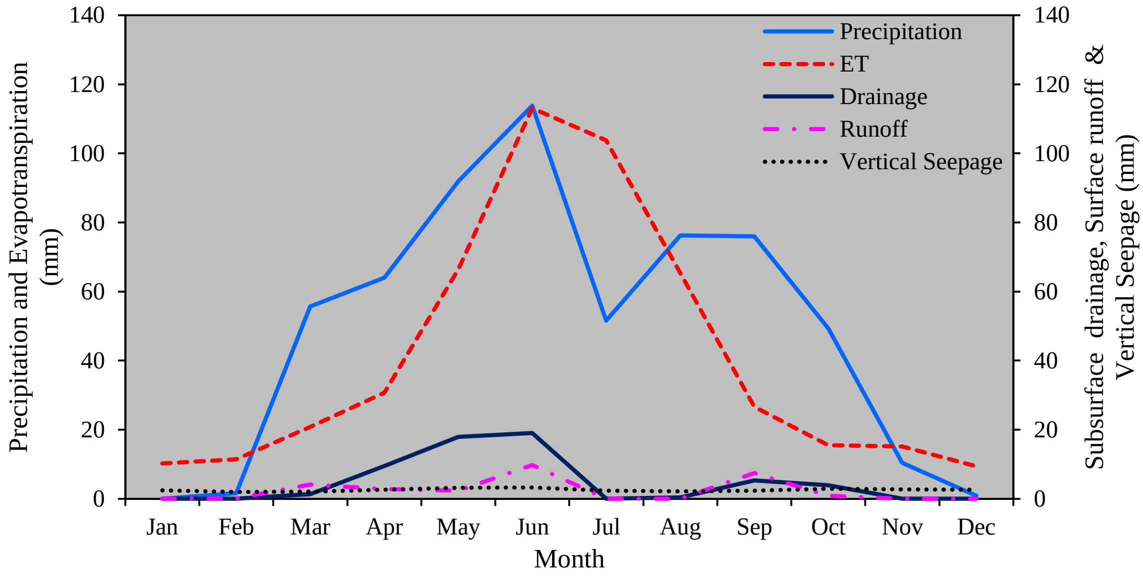


Figure 47. Monthly field water balance in wheat-corn production under controlled drainage.

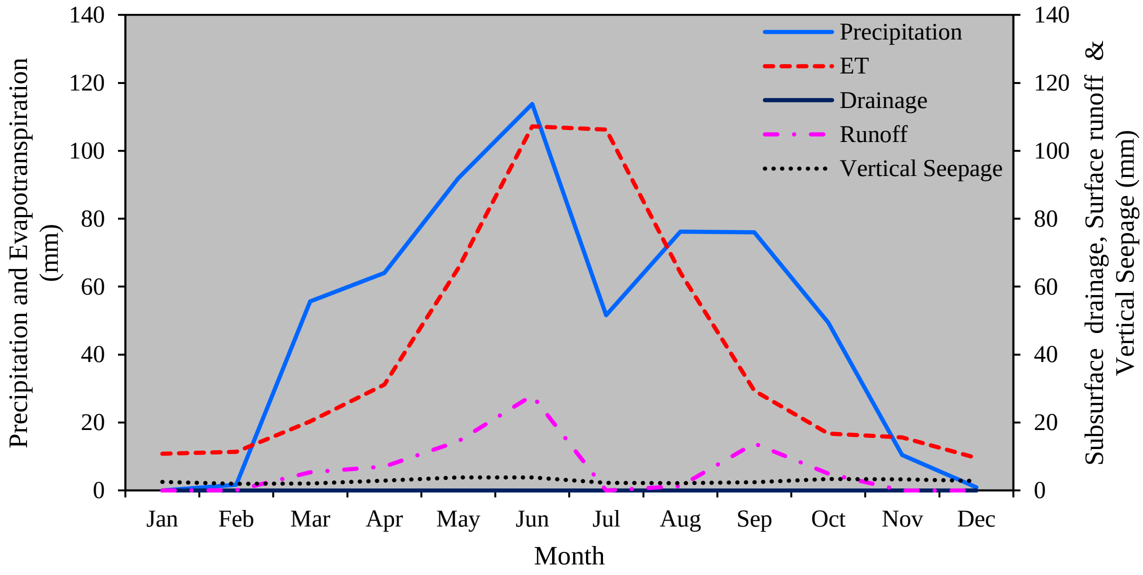


Figure 48. Monthly field water balance in wheat-corn production under undrained condition.

4.2.4.7 Wheat-Soybean Rotation

Average monthly ET, precipitation, subsurface drainage, surface runoff, and vertical seepage for the 12-year period for wheat-soybean under conventional drainage, controlled drainage, and undrained conditions are plotted in Figure 49, Figure 50, and Figure 51, respectively. Drainage outflow under conventional drainage was predicted higher for May, June, September, and October, with of values 18.3 mm, 27.0 mm, 14.5 mm, and 12.5 mm, respectively. Likewise, drainage outflow under controlled drainage was predicted higher for May, June, and September with values of 19.5 mm, 19.8 mm, and 9.9 mm. Drainage outflow volume reduction of 27% was observed for June in controlled drainage compared to conventional drainage. Due to higher ET and low, average monthly precipitation in month of July, drainage outflow in both drainage conditions was very low.

Average monthly surface runoff for undrained condition was predicted higher for May, June, and September with values of 12.6 mm, 28.1 mm, and 18.1 mm, respectively. For all other months, surface runoff was very low for the undrained condition. For conventional and controlled drainage conditions, surface runoff was predicted higher for June with value of 8.2 mm in conventional drainage, and 9.7 mm in controlled drainage. Surface runoff reduction of 70.8% and 65.4% was predicted in conventional drainage compared to undrained condition and controlled drainage for the month of June. No considerable difference in vertical seepage was predicted between conventional drainage, controlled drainage, and undrained conditions.

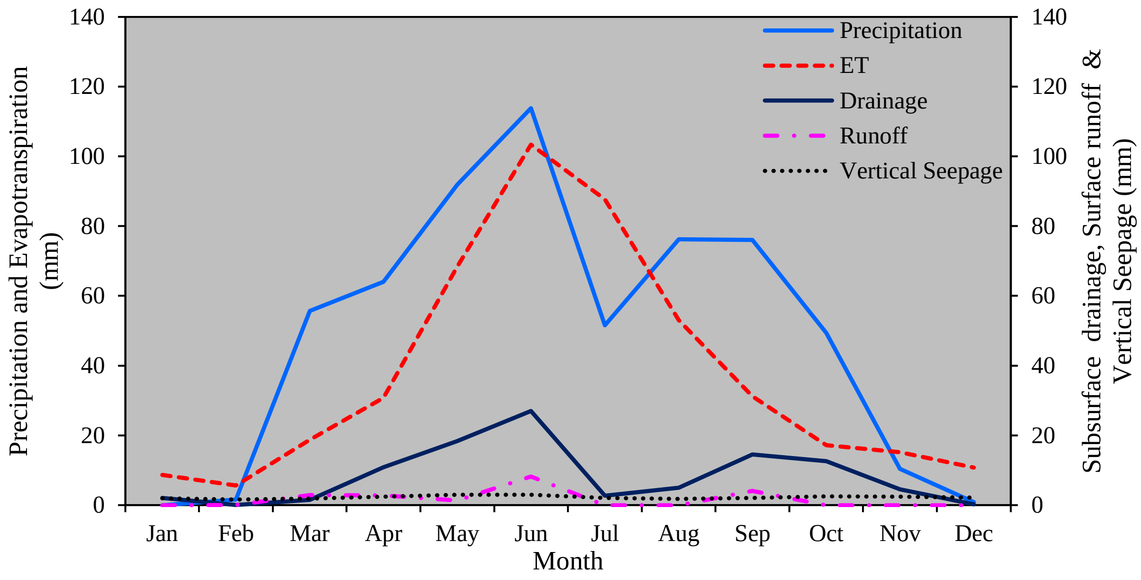


Figure 49. Monthly field water balance in wheat-soybean production under conventional drainage.

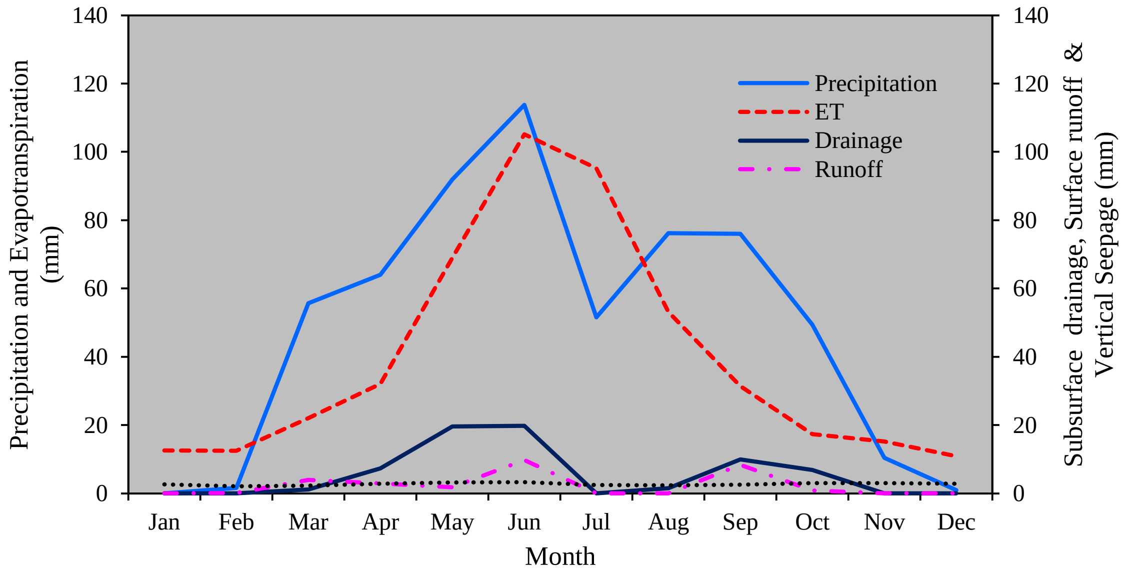


Figure 50. Monthly field water balance in wheat-soybean production under controlled drainage.

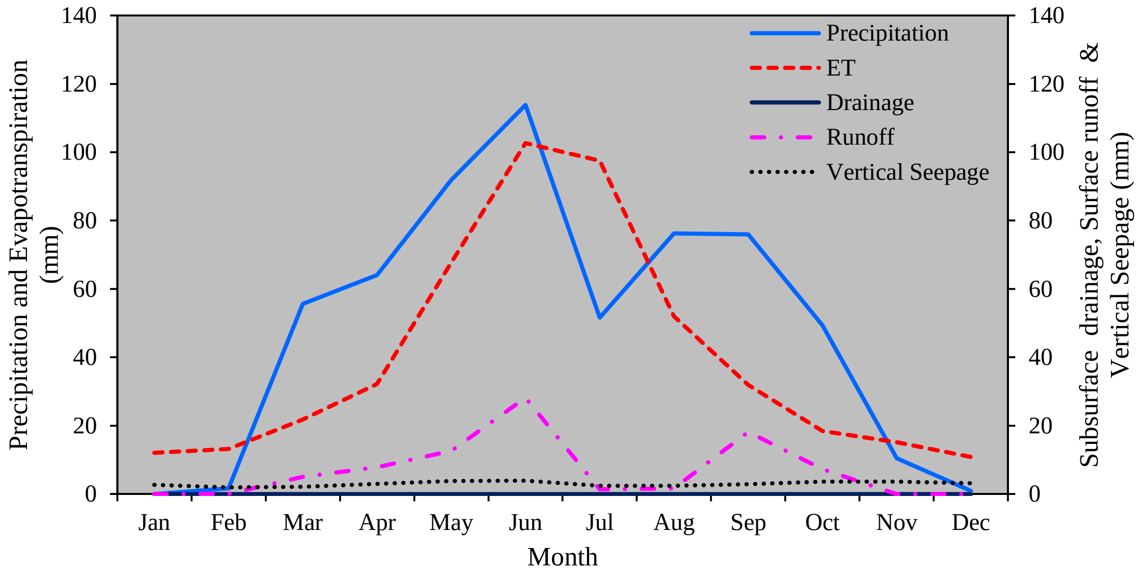


Figure 51. Monthly field water balance in wheat-soybean production under undrained condition.

4.2.5 Monthly Water Table Depth

Predicted average monthly water table depths for continuous corn, corn-soybean, soybean-corn, corn-wheat, soybean-wheat, wheat-corn, and wheat-soybean under conventional drainage, controlled drainage, and undrained conditions are shown in Figure 52, Figure 53, and Figure 54. In conventional drainage conditions, average monthly water table depth for June was the same for all cropping practices, with an average value of 951 mm. Water table depth for continuous corn, corn-soybean, and soybean-corn had similar trends from July to December. However, water table depth was low in continuous corn from August to November, with the lowest value of 1615 mm in August. Likewise, water table depth for corn-wheat, soybean-wheat, wheat-corn, and wheat-soybean was predicted with similar trends from July to December with slight variation in water table depth for wheat-soybean production from September to November. Water table depth for all these cropping practices mentioned above dropped below 1200 mm from July to August.

Similar trends in controlled drainage and undrained condition were predicted. Water table depth in controlled drainage condition for June was predicted lowest for corn-wheat, with a value of 921 mm, and highest for corn-soybean, with a value of 866 mm. Considerable variation in water table depth was predicted between cropping practices from July to December. Lowest water table depth for continuous corn for August was 1575 mm, and highest water table depth for wheat-soybean was 1343 mm. In undrained conditions, water table depth for all cropping practices were predicted below 800 mm in June. The lowest water table depth was predicted in August for continuous corn, with a value of 13666 mm, and the height water table depth was predicted for wheat-soybean, with a value of 1245 mm.

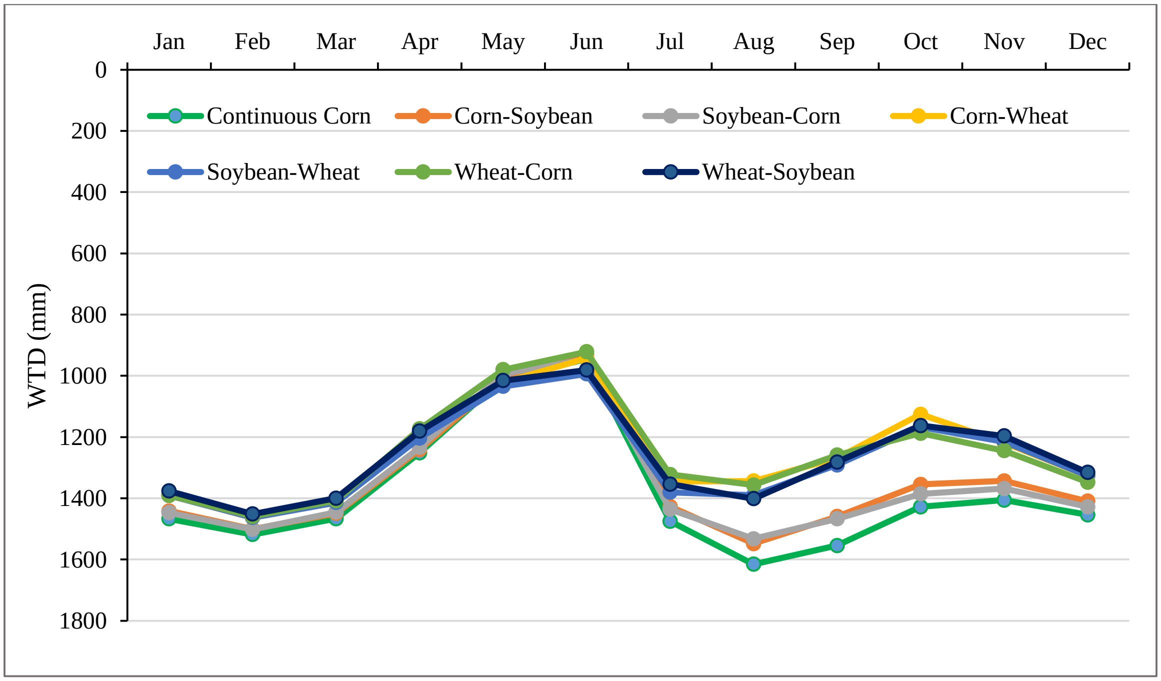


Figure 52. Average monthly water table depth under conventional drainage.

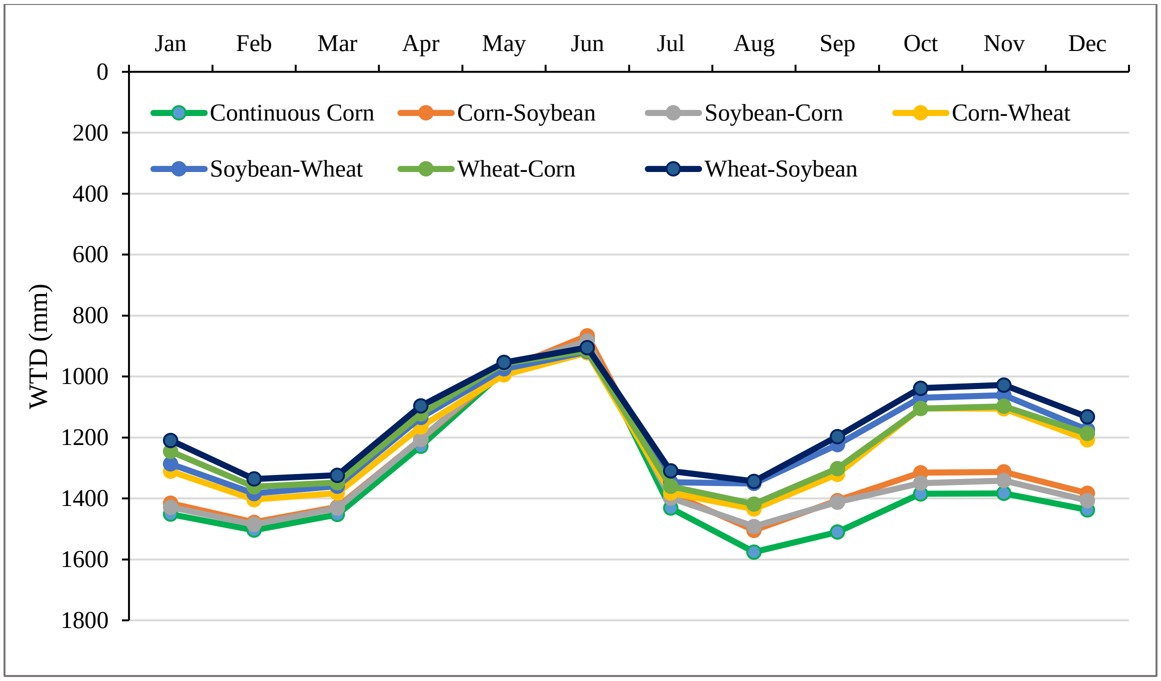


Figure 53. Average monthly water table depth variation under controlled drainage.

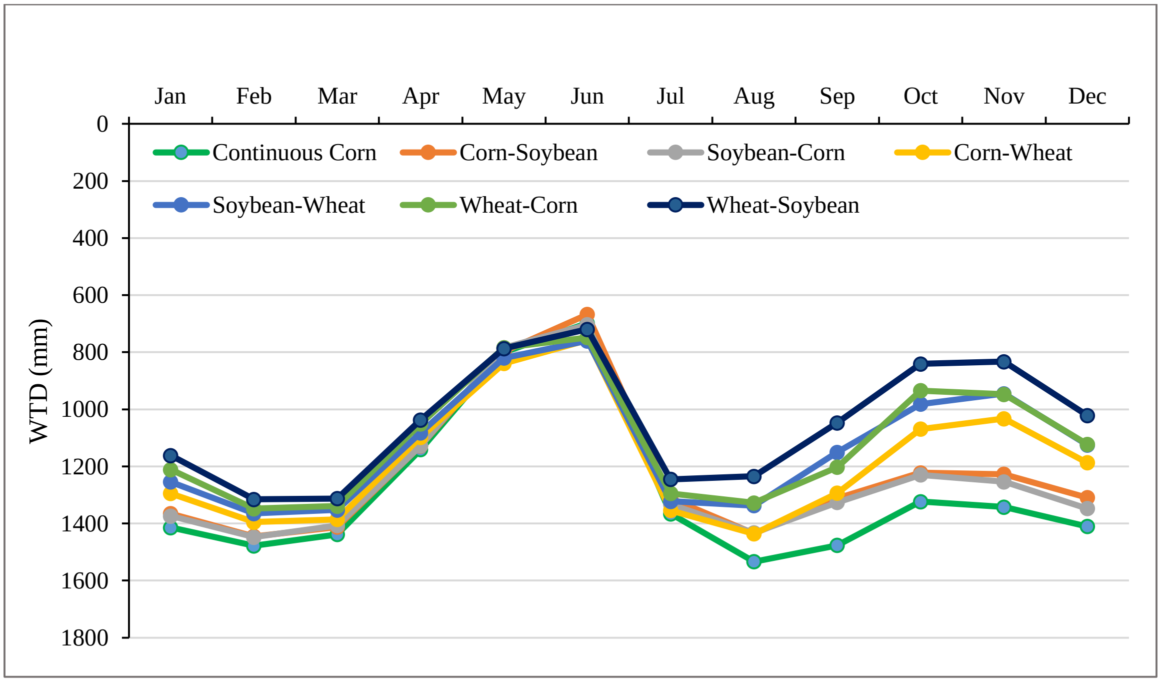


Figure 54. Average monthly water table depth variation under undrained condition.

4.3 Long-term Relative Crop Yield

Predicted 12-year average relative crop yields for different drainage conditions for EhA Trent series silty clay loam soil at Clay County, SD are plotted as a function of cropping practices in Figure 55. Crop relative yield can be defined as the ratio of actual crop yield (accounts soil water stress factors) to the potential crop yield (Skaggs et al., 2006). Long-term average relative crop yield (kg/ha) was computed as the product of predicted crop yield (%) and potential yield (kg/ha). The average relative crop yield for controlled drainage and conventional drainage conditions for all cropping practices was observed to have high crop yield compared to undrained conditions. For conventional and controlled drainage, relative yield percentage of corn-soybean and soybean-corn was higher compared to all other cropping practices. Average relative crop yield for the simulated 12-year period for soybean-corn under conventional and controlled drainage was 81.6% (i.e. 6542 kg/ha) and 81.8% (i.e. 6649 kg/ha), respectively. Likewise, predicted corn-soybean relative crop yield percentage was 80.9% (i.e. 66341 kg/ha) and 81.7 % (i.e. 6528 kg/ha) in conventional and controlled drainage, respectively. The average relative yield percentage for continuous corn under conventional and controlled drainage was predicted 75.8% (9854 kg/ha) and 71.2% (9261 kg/ha), respectively. The average relative yield of soybean-wheat and wheat-soybean was also observed higher under conventional and controlled drainage with values of 81.1% (3605 kg/ha) and 80.3% (3540 kg/ha) under conventional and 80.5% (3594 kg/ha) and 78.1% (3447 kg/ha) under controlled drainage, respectively.

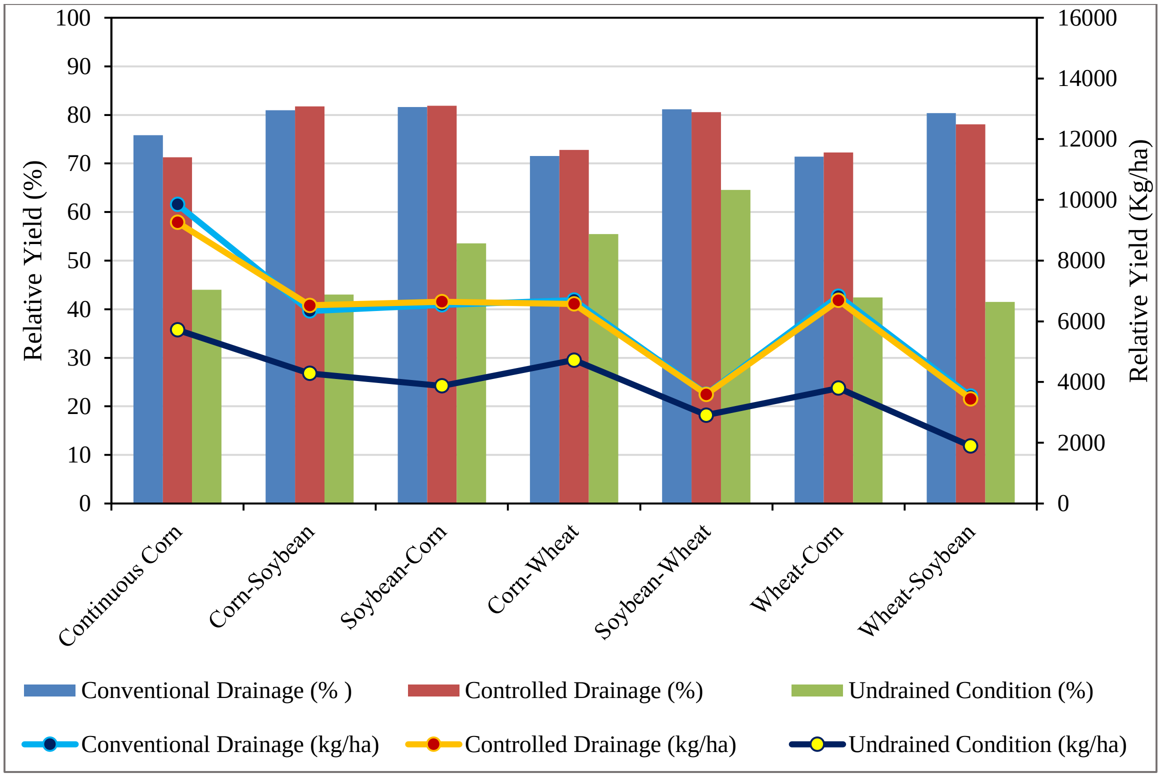


Figure 55. Average annual relative crop yield for different cropping practices.

4.4 2-Year Average of Crop Yield for Different Crop Rotations

2-year average of % relative crop yield for each crop rotation under conventional drainage, controlled drainage, and undrained conditions from period 2004-2015 are plotted in Figure 56, Figure 57, and Figure 58. 2-year average percentage relative crop yield of corn-soybean and soybean corn indicated higher percentage relative crop yield under conventional drainage for period 2014-2015, with maximum value of 96.1% compared to controlled drainage, which has maximum value of 93.9%. However, the average percentage relative crop yield was higher for controlled drainage for period 2004-2015 compared to conventional drainage. The lowest percentage relative yield for period 2004-2015 was observed in undrained condition.

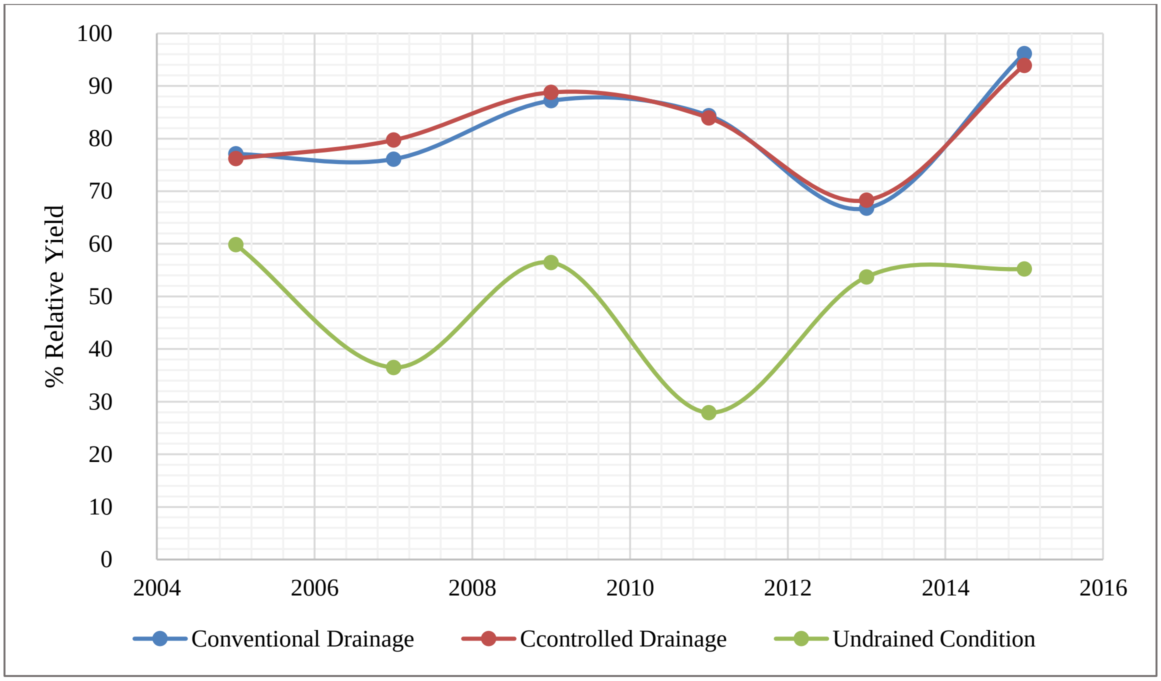


Figure 56. 2-year average of corn-soybean and soybean-corn relative crop yield.

2-year average percentage relative crop yield of corn-wheat and wheat-corn rotation indicated higher percentage relative crop yield for period 2014-2015, with value of 88.1% and lower percentage of crop relative for period 2012-2013, with value of 53.1% under conventional drainage. In controlled drainage, the maximum value was predicted 84.8% for period 2014-2015 and lowest value was predicted 58.4% for period 2012-2013. For undrained conditions, the percentage relative crop yield from 2004-2015 was predicted low compared to controlled and conventional drainage. It has maximum value of 72.1% for period 2014-2015 and minimum value of 27.4% for period 2006-2007.

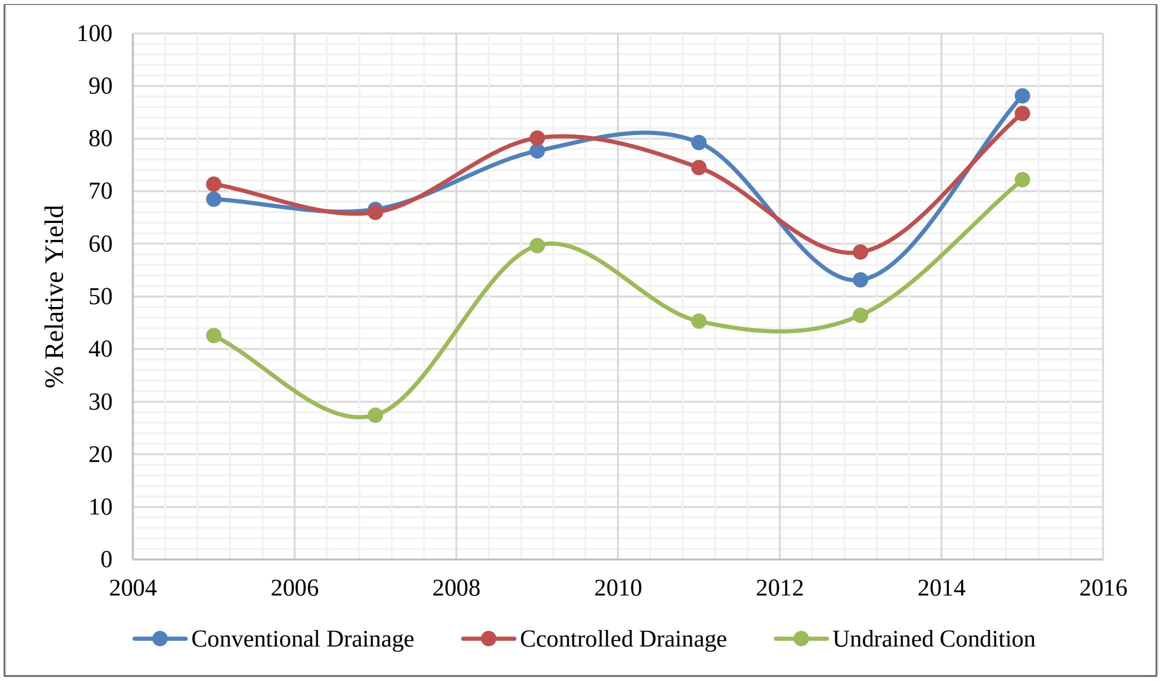


Figure 57. 2-year average of corn-wheat and wheat-corn relative crop yield.

For soybean-wheat and wheat-soybean, 2-year average relative crop yield percentage indicated higher percentage relative crop yield for period 2014-2015 for both conventional and controlled drainage, with values of 93.2% and 88.6%, respectively. The minimum value was observed for period 2012-2013 for both drainage conditions, with value of 69.0% and 69.3%, respectively. For the undrained condition, the maximum value was observed for period 2008-2009, with value of 70.1% and minimum was observed for period 2006-2007, with value of 38.8%.

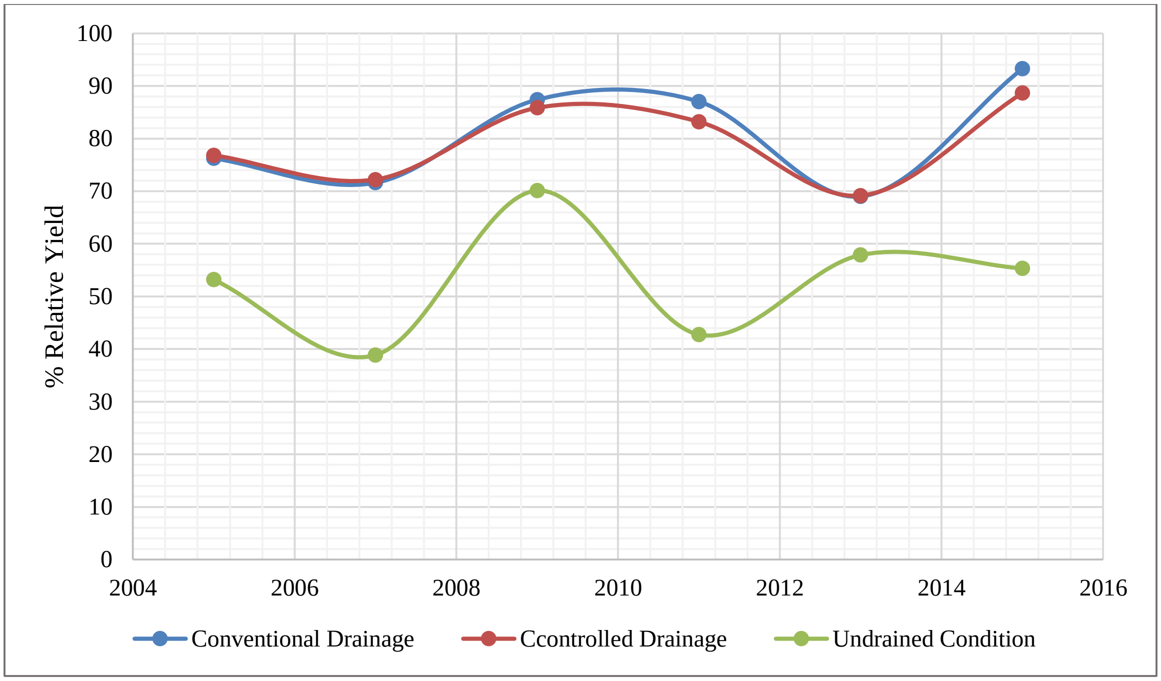


Figure 58. 2-year average of corn-wheat and wheat-corn relative crop yield.

4.5 Economic Analysis of Subsurface Drainage Impacts on Crop Yield

Average net annual return ($/ha/yr) for the 12-year study period for different cropping practices under conventional drainage, controlled drainage, and undrained conditions are plotted in Figure 59, Figure 60, and Figure 61. Economic analysis results indicated higher net annual return for soybean-corn cropping system under controlled drainage compared to conventional drainage. Net annual return per ha for soybean-corn under controlled drainage was $696 whereas it was $664 for the same cropping practice under conventional drainage system. This variation in net annual return was due to high soybean yield in soybean-corn rotation under controlled drainage. In both drainage conditions, soybean-corn rotation was found to have higher net annual return compared to all other cropping practices.

Based on potential yield and predicted average annual crop yield, wheat-soybean and soybean-wheat were found to have low net return due to low crop yield in conventional and controlled drainage conditions. Under undrained condition, corn-soybean rotation was found to yield average net annual return of $135 whereas all other cropping practices indicated very low return.

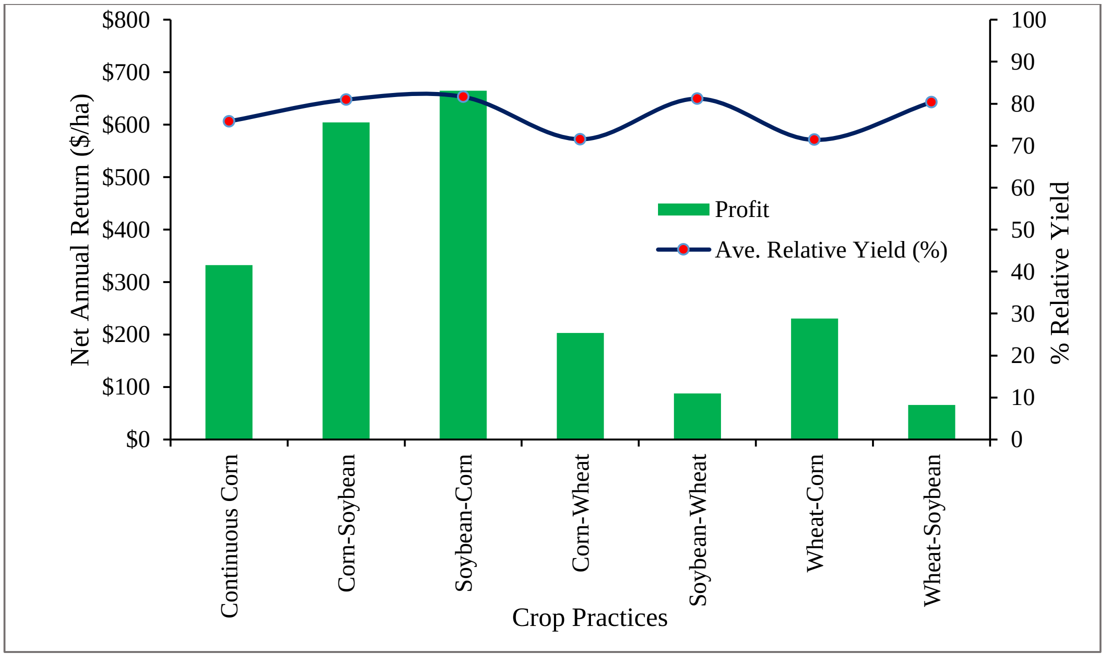


Figure 59. Net annual return per hectare from conventional drainage system.

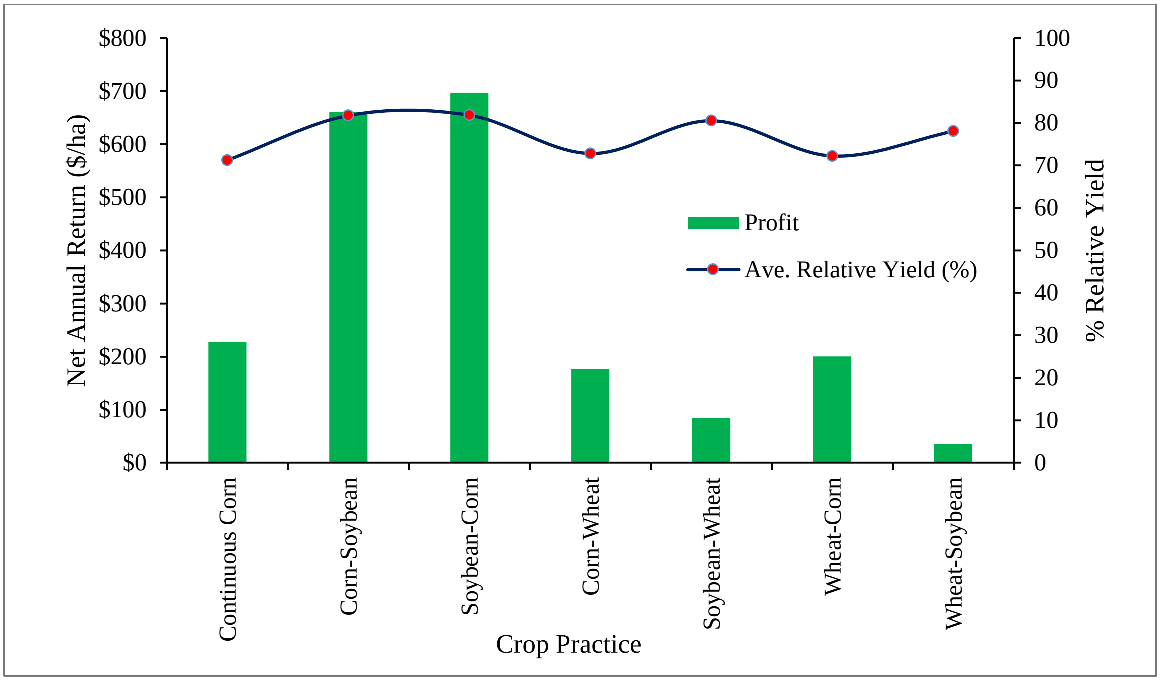


Figure 60. Net annual return per hectare from controlled drainage system

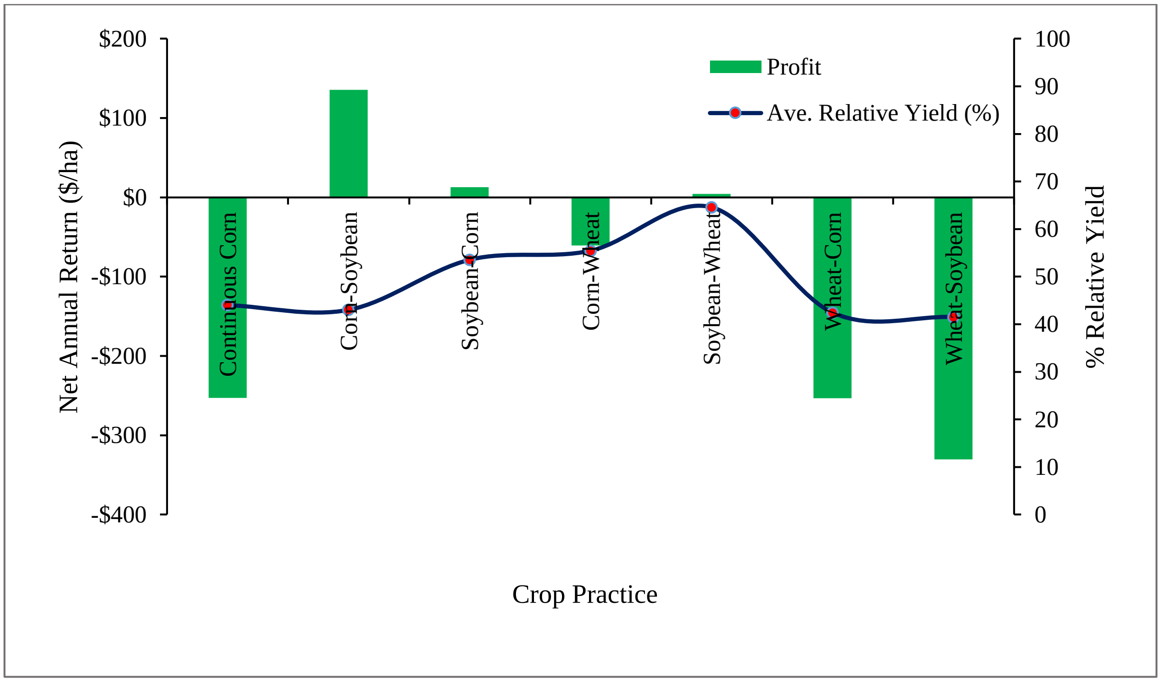


Figure 61. Net annual return per hectare from undrained fields

5 LIMITATIONS OF THE STUDY

Model simulation was performed for period 2004-2015 in which the majority of the period was wet period except 2012. In 2012, total rainfall of 277 mm was received, whereas the average rainfall for the period 2004-2015 was 588 mm. DRAINMOD predicts percentage relative crop yield accounting excess soil-water stress, deficit soil-water stress, and planting delay conditions. As the majority of simulation period was wet period, it has impacted the water yield (surface runoff and drainage) and percentage relative crop yield for different crop rotation under drained and undrained conditions. Also, no fertilizer applications were taken into consideration during model simulations and therefore, simulation of percentage relative crop yield for continuous corn is only based on field water condition. In practice, soil cannot support continuous corn practice without fertilizer. Therefore, the results should be interpreted with caution.

Another important factor that needs to be accounted for in the analysis of field water balance and relative crop yield is drainage intensity. In subsurface drainage system design, two important factors- drain depth and drain spacing determines the drainage intensity and therefore, it is considered as an influential factor affecting drainage outflow. In drained conditions, high drainage intensity results in more drainage outflow and reduces surface runoff volume. In this research, the weir settings for different cropping practices under controlled drainage was varied and drainage configuration related to drain depth and drain spacing were used as per field set up. Thus, the effect of single drainage intensity was employed in this research for predicting percentage relative crop yield and water yield. To account the effect of varying drainage intensities on percentage relative crop yield and water yield, it should be better to perform simulations at different drain depth and drain spacings which can provide better insight on drainage intensity effect and best drainage intensity design for effective water management and percentage relative crop yield predictions.

Also, relative crop yield of different crops was not found significantly different under conventional and controlled drainage conditions; this may be due to the weather conditions of the simulation period in which majority of years were wet years. As the model accounts crop stresses resulting from excess or deficit soil water and planting delay conditions, the model predicted yield is percentage of the maximum obtainable yield with no stresses. Thus, the effect of other factors such as tillage, fertilizer application, and field conditions (e.g. initial soil organic content, weeds, and diseases) were not considered in the simulation.

In this research, crops (corn, soybean, or wheat) was assumed to have been planted on entire land available for cropping during model simulation of relative crop yield. In real practice a producer with a large farmland would not have their cropland in one crop but may grow different crops on different parts of the land each year.

6 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

6.1 Conclusions

The objective of this study was to predict field water balance, crop yield response, and economics of subsurface drainage for different cropping practices under conventional drainage, controlled drainage, and undrained conditions using a field scale hydrologic model, DRAINMOD. Through 12-year (2004-2015) simulations, the long-term annual averages, monthly patterns, water balance components for different crop practices, crop yield, and economics of drainage systems were predicted and discussed.

Average annual subsurface drainage outflow for conventional drainage and controlled drainage showed considerable reduction in drainage volume in continuous corn production, corn-soybean, and soybean-corn under controlled drainage compared to all other cropping practices under controlled and conventional drainage. Average annual drainage outflow for continuous corn, corn-soybean, soybean-corn, corn-wheat, soybean-wheat, wheat-corn, and wheat-soybean cropping practices under controlled drainage showed drainage volume reduction of 28%, 24%, 24%, 52%, 37%, 54%, and 40%, respectively, compared to conventional drainage. Higher drainage volume reduction in controlled drainage condition resulted from the raising of weir height to 60 cm (depth from soil surface) in the control structure during growing seasons. In conventional drainage, no restrictions were applied to drainage outflow which creates more temporary water storage in the soil profile through quick removal of excess water and promotes more water infiltration, resulting reduction in surface runoff volume. Thus, simulation results showed substantial reduction in surface runoff in conventional drainage compared to controlled drainage and undrained conditions. Surface runoff reduction of 72%, 75%, 71%, and 76% was predicted in continuous corn, corn-soybean, soybean-corn, and wheat-soybean rotation, respectively, under conventional drainage compared to undrained conditions. Likewise, in controlled drainage reduction in runoff volume was found to be 65%, 68%, 65%, and 66% in continuous corn, corn-soybean, soybean-corn, and wheat-soybean respectively, compared to undrained conditions. ET water loss for controlled and undrained conditions was higher compared to conventional drainage for all cropping practices.

Average monthly simulation results for 12-year period showed high ET water loss during the month of May to August for all cropping practices. In conventional drainage, maximum ET was observed for continuous corn in June and July, with values of 127.3 mm and 123.2 mm, respectively, compared to all other cropping practices. Drainage water loss was also higher in May and June. Maximum drainage outflow was predicted in wheat-corn rotation, with values of 20.9 mm and 29.9 mm for May and June, respectively. In controlled drainage, 57.0% of drainage volume reduction predicted in wheat-corn rotation for June compared to conventional drainage. Surface runoff mostly occurred during high rainfall events and simulation results showed that the conventional system can reduce runoff volume by 86.7%, and 70.0%, respectively, in May and June for soybean-corn practice compared to undrained condition. Similarly, controlled drainage can reduce 86.6% and 63.3%, respectively, in May and June.

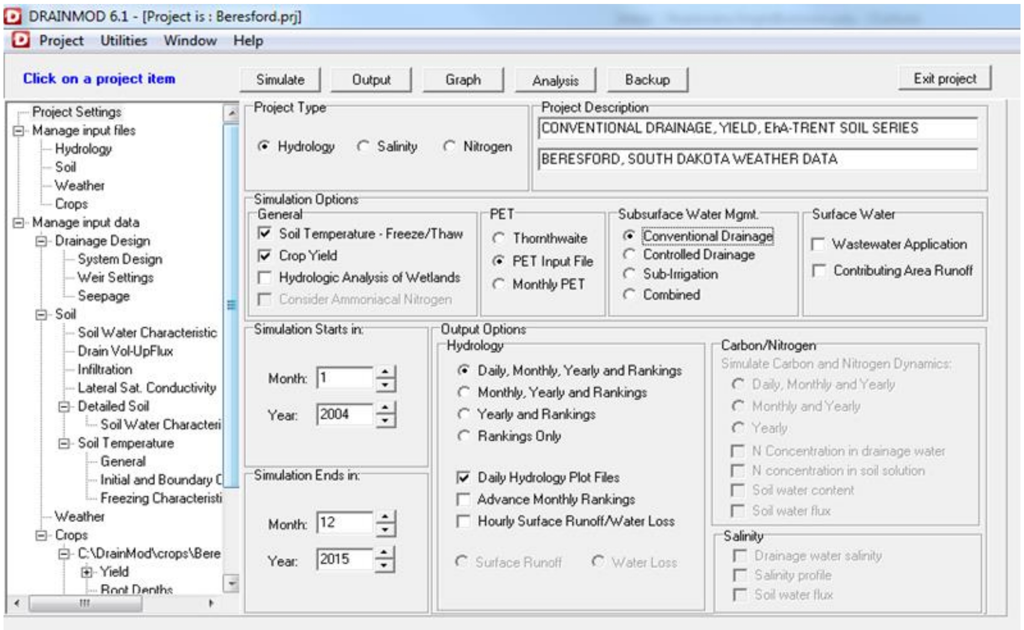
Predicted relative crop yield percentage showed higher crop yield response in soybean-corn, and corn-soybean rotation under both controlled and conventional drainage compared to all other cropping practices under conventional drainage, controlled drainage, and undrained conditions. The relative crop yield percentage for soybean-corn and corn-soybean under conventional drainage was 81.6% (i.e. 6542 kg/ha) and 80.9% (6341 kg/ha), respectively, and under controlled drainage, relative yield was 81.8% (6649 kg/ha) and 81.7% (6528 kg/ha), respectively. Economic analysis of subsurface drainage showed considerable variation in net annual returns for the three conditions. Results indicated higher average annual return from soybean-corn cropping practices under controlled drainage compared to conventional drainage and undrained conditions.

6.2 Recommendations for Future Work

- The reliability of DRAINMOD model predictions increases when used with many years of field observed data. In this research, model was calibrated and validated using two years of data and long-term simulation was conducted using 12 years of weather data. It is highly recommended to use longer period of data for model calibration and long-term simulations.
- Soil properties used in DRAINMOD are highly sensitive in nature and therefore, it is recommended to use accurate field measured soil data representative of the study site instead of using estimated soil property data.
- It is highly recommended to employ weather data from weather stations that were located nearby research sites for model calibration, validation, and long-term simulation to improve model predictions.

7 APPENDICES

7.1 Appendix A: DRAINMOD Model



Project Type
● Hydrology ○ Salinity ○ Nitrogen

Project Description
CONVENTIONAL DRAINAGE, YIELD, EhA-TRENT SOIL SERIES
BERESFORD, SOUTH DAKOTA WEATHER DATA

Simulation Options

General
☑ Soil Temperature - Freeze/Thaw
☑ Crop Yield
☐ Hydrologic Analysis of Wetlands
☐ Consider Ammoniacal Nitrogen

PET
○ Thornthwaite
● PET Input File
○ Monthly PET

Subsurface Water Mgmt.
● Conventional Drainage
○ Controlled Drainage
○ Sub-Irrigation
○ Combined

Surface Water
☐ Wastewater Application
☐ Contributing Area Runoff

Simulation Starts in:
Month: 1
Year: 2004

Simulation Ends in:
Month: 12
Year: 2015

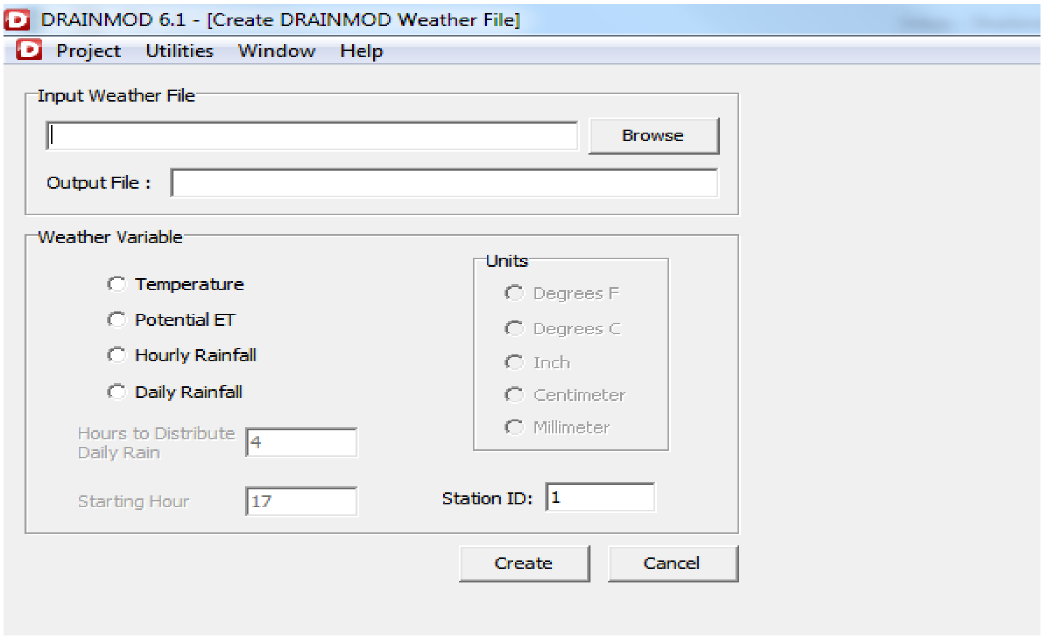
Output Options

Hydrology
● Daily, Monthly, Yearly and Rankings
○ Monthly, Yearly and Rankings
○ Yearly and Rankings
○ Rankings Only
☑ Daily Hydrology Plot Files
☐ Advance Monthly Rankings
☐ Hourly Surface Runoff/Water Loss
○ Surface Runoff ○ Water Loss

Carbon/Nitrogen
Simulate Carbon and Nitrogen Dynamics:
○ Daily, Monthly and Yearly
○ Monthly and Yearly
○ Yearly
☐ N Concentration in drainage water
☐ N concentration in soil solution
☐ Soil water content
☐ Soil water flux

Salinity
☐ Drainage water salinity
☐ Salinity profile
☐ Soil water flux

Figure 54. DRAINMOD Model Interface



Input Weather File

Output File :

Weather Variable
○ Temperature
○ Potential ET
○ Hourly Rainfall
○ Daily Rainfall

Units
○ Degrees F
○ Degrees C
○ Inch
○ Centimeter
○ Millimeter

Hours to Distribute Daily Rain: 4

Starting Hour: 17

Station ID: 1

Figure 55. DRAINMOD Utilities Program Interface

7.2 Appendix B: DRAINMOD Soil Data

```
5 layer Soil EhA Egan silty clay loam
1220
   0.4910      0.00
   0.4600    -25.00
   0.4300    -50.00
   0.4070    -75.00
   0.3880   -100.00
   0.3610   -150.00
   0.3410   -200.00
   0.3080   -330.00
   0.2830   -500.00
   0.2460  -1000.00
   0.1830  -5000.00
   0.1550 -15000.00
   0.0000    0.0000    0.5000
   3.0000    0.0060    0.5000
   6.0000    0.0220    0.5000
   9.0000    0.0500    0.5000
  12.0000    0.0880    0.5000
  15.0000    0.1380    0.5000
  20.0000    0.2460    0.4080
  25.0000    0.3800    0.3005
  30.0000    0.5360    0.2169
  35.0000    0.7130    0.1678
  40.0000    0.9120    0.1397
  45.0000    1.1320    0.1168
  60.0000    1.9250    0.0717
  75.0000    2.8900    0.0368
  90.0000    4.0100    0.0177
 120.0000    4.5710    0.0071
 150.0000    8.3870    0.0010
 200.0000   14.4510    0.0000
 500.0000   51.3870    0.0000
1000.0000  100.0000    0.0000
10
    0.00      0.00      1.75
   10.00      0.05      1.75
```

```
    20.00     0.10     1.75
    40.00     0.25     1.75
    60.00     0.30     1.75
    80.00     0.42     1.75
   100.00     0.45     1.75
   150.00     1.45     1.75
   200.00     1.45     1.75
  1000.00     1.45     1.75

*TOP AND BOTTOM OF LAYER
    0.0    20.0
 *NUMBER OF POINTS IN LAYER
  12
  0.491        0.0
  0.460       25.0
  0.430       50.0
  0.407       75.0
  0.388      100.0
  0.361      150.0
  0.341      200.0
  0.308      330.0
  0.283      500.0
  0.246     1000.0
  0.183     5000.0
  0.155    15000.0
 *TOP AND BOTTOM OF LAYER
   20.0    66.0
 *NUMBER OF POINTS IN LAYER
  12
  0.459        0.0
  0.437       25.0
  0.412       50.0
  0.390       75.0
  0.372      100.0
  0.345      150.0
  0.324      200.0
  0.289      330.0
  0.262      500.0
  0.223     1000.0
```

```
 0.158      5000.0
 0.130     15000.0
*TOP AND BOTTOM OF LAYER
   66.0    86.0
*NUMBER OF POINTS IN LAYER
 12
 0.456         0.0
 0.434        25.0
 0.410        50.0
 0.388        75.0
 0.370       100.0
 0.342       150.0
 0.321       200.0
 0.285       330.0
 0.257       500.0
 0.217      1000.0
 0.151      5000.0
 0.124     15000.0
*TOP AND BOTTOM OF LAYER
   86.0   137.0
*NUMBER OF POINTS IN LAYER
 12
 0.389         0.0
 0.372        25.0
 0.355        50.0
 0.340        75.0
 0.329       100.0
 0.311       150.0
 0.297       200.0
 0.273       330.0
 0.255       500.0
 0.226      1000.0
 0.173      5000.0
 0.147     15000.0
*TOP AND BOTTOM OF LAYER
  137.0   137.0
*NUMBER OF POINTS IN LAYER
 12
 0.389         0.0
```

```
  0.372      25.0
  0.355      50.0
  0.340      75.0
  0.329     100.0
  0.311     150.0
  0.297     200.0
  0.273     330.0
  0.255     500.0
  0.226    1000.0
  0.173    5000.0
  0.147   15000.0
 *TOP AND BOTTOM OF LAYER
   137.0   137.0
 *NUMBER OF POINTS IN LAYER
  12
0.38941       0.0
0.37179      25.0
0.35454      50.0
0.34032      75.0
0.32863     100.0
0.31055     150.0
0.29708     200.0
0.27349     330.0
0.25458     500.0
0.22558    1000.0
0.17260    5000.0
0.14651   15000.0
 *TOP AND BOTTOM OF LAYER
   137.0   152.0
 *NUMBER OF POINTS IN LAYER
  12
0.38869       0.0
0.37129      25.0
0.35405      50.0
0.33977      75.0
0.32799     100.0
0.30973     150.0
0.29611     200.0
0.27223     330.0
```

```
0.25309       500.0
0.22379      1000.0
0.17046      5000.0
0.14435     15000.0
```

7.3 Appendix C: DRAINMOD Crop Input Data

```
Corn

*** First Possible and last possible dates for crop ***
  1 365
*** Weir Control ***
 1
 1 30 1 30 1 3015120 1 7515 60 1 60 1 60 1 6012120 1 30 1 30
*** Trafficability ***
 326 526 720              2.50      2.00      1.00
 821 922 720               3.0      2.00      1.00
*** Crop ***
 4251015       30.00
 4251015
*** Root Depths ***
12
 1 1  3.00 4 1  3.00 5 4  3.00 6 3 10.00 618 20.00 630 35.00 712 40.00 726 40.00
 822 40.001010 15.001011  3.001231  3.00
*** Yield Inputs ***
 1
  125  169    0.8100    2.0000  201.0000   30.0000
26 7       11.16000  -1.17000    .05800   -.00050 100.00000   1.50000
100.0000  1.2200102.0000  0.7500 120 173   1
  0 290.20 30 490.22 50 690.32 70 890.19 901090.081101290.021301300.00
0.000.000.000.000.000.500.501.001.001.001.001.752.002.001.301.301.301.301.301.20
1.000.500.000.000.000.00
*** Salinity Modifications ***
Threshold     Slope
    0.000000E+00    0.000000E+00
*** Irrigation Water Salinity ***
  0
```

```
Soybean
*** First Possible and last possible dates for crop ***
  1 365
*** Weir Control ***
 1
 1 30 1 30 1 303012015 7530 60 1 60 1 603012015 30 1 30 1 30
*** Trafficability ***
 4 5 6 5 720          3.0     2.00     1.00
 9161017 720          3.00     2.00     1.00
*** Crop ***
 4 51116      30.00
 4 51116
*** Root Depths ***
15
 1 1  3.00 5 5  3.00 520  3.00 6 4  8.00 618 12.00 630 20.00 716 25.00 728 30.00
 811 35.00 825 35.00 9 8 30.00 922 20.0010 3  5.0010 4  3.001231  3.00
*** Yield Inputs ***
 1
  147  153    .50000    1.0000   1.80000  30.00000
29 8       11.16000  -1.17000    .05800   -.00050 100.00000   1.50000
100.0000  7.2000103.0000  0.7000 140 140   1
  0  40.19  5 390.13 40 740.19 75 890.26 901140.251151340.081351440.011451450.00
0.010.030.030.030.030.050.050.050.100.100.100.150.150.150.150.200.200.200.100.10
0.100.050.050.050.020.020.020.000.00
*** Salinity Modifications ***
Threshold     Slope
    4000.000000    2.500000E-02
*** Irrigation Water Salinity ***
 12
  1  1     400.0
  2  1     400.0
  3  1     400.0
  4  1     400.0
  5  1     400.0
  6 15     400.0
  7 23     400.0
  8  3     400.0
  9  3     400.0
```

```
 10  4     400.0
 11  5     400.0
 12 31     400.0

Wheat
*** First Possible and last possible dates for crop ***
  1 365
*** Weir Control ***
 1
 1 30 1 3015 12 1 7515 60 1  626 30 1  3 1 30 1 30 1 30 1 30
*** Trafficability ***
 915 131 820              3.9       1.2       2.0
12311231 820              3.9       1.2       2.0
*** Crop ***
 930 2 2       30.00
 930 2 2
*** Root Depths ***
 8
 1 1 42.00 1 8 30.00 128 15.00 3 2  3.0010 1  3.001031 14.0011 9 30.001231 42.00
*** Yield Inputs ***
 1
   95  126    .87000   1.00000   1.70000  15.00000
32 7         .00000    .00000    .00000    .00000    .00000   1.00000
100.0000  1.2200100.0000   .7100  92 120   1
  0 29 .19 30 49 .13 50 64 .19 65 79 .26 80 95 .25 96114 .08115120 .01
 .00 .00 .00 .00 .00 .00 .05 .051.001.001.001.001.752.102.101.301.301.301.301.30
1.201.00 .50 .00 .00 .00 .00 .00 .00 .00 .00 .00
*** Salinity Modifications ***
Threshold     Slope
     4800.000000    8.880000E-03
*** Irrigation Water Salinity ***
 12
  1  1     400.0
  2  1     400.0
  3  1     400.0
  4  1     400.0
  5  1     400.0
  6 15     400.0
  7 23     400.0
```

```
 8  3     400.0
 9  3     400.0
10  4     400.0
11  5     400.0
12 31     400.0
```

7.4 Appendix D: Weir Settings

Adjusted Weir Settings for Corn production-

Month	Day	Depth (From Soil Surface)
January	1	30 cm
February	1	30 cm
March	1	30 cm
April	15	120 cm
May	1	75cm
June	15	60 cm
July	1	60 cm
August	1	60 cm
September	1	60 cm
October	12	120 cm
November	1	30 cm
December	1	30 cm

**Plantation on- May 1 and Harvesting on- October 28

Adjusted Weir Settings for Soybean production-

Month	Day	Depth (From Soil Surface)
January	1	30 cm
February	1	30 cm
March	1	30 cm
April	30	120 cm

May	15	75 cm
June	30	60 cm
July	1	60 cm
August	1	60 cm
September	30	120 cm
October	15	30 cm
November	1	30 cm
December	1	30 cm

**Plantation on- May 15 and Harvesting on- October 15

Adjusted Weir Settings for Wheat production-

Month	Day	Depth (From Soil Surface)
January	1	30 cm
February	1	30 cm
March	15	120 cm
April	1	75 cm
May	15	60 cm
June	1	60 cm
July	26	30 cm
August	1	30 cm
September	1	30 cm
October	1	30 cm
November	1	30 cm
December	1	30 cm

**Plantation on- April 1 and Harvesting on- July 30

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